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July 30 – August 2. Coeur d'Alene Resort, Coeur d'Alene, Idaho

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Council on Forest Engineering

PROCEEDINGS OF
THE 29TH COUNCIL ON FOREST ENGINEERING CONFERENCE

July 30 – August 2, 2006
Coeur d'Alene Resort
Coeur d'Alene, Idaho

Compiled and Edited by
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ACKNOWLEDGEMENTS

Many colleagues and organizations have contributed to the preparation of this conference. We thank The University of Idaho, The University of Montana, and the Council on Forest Engineering Office for hosting this conference. We also thank the sponsors (IUFRO Division 3, Plum Creek Timber Company, Potlatch Corporation, Forest Capital Partners, LLC) for their monetary donations and help in organizing our field trips.

Lastly, we wish to acknowledge the efforts of all the authors involved in these proceeding papers and presentations.

Han-Sup Han

Woodam Chung

Study of production-cost of Mule Logging and products amount of traditional processing method- Case study in Northeren forests of Iran, Nowshahr*

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Abstract
Animal logging is one of the traditional logging systems, some researches on production-cost of Animal Logging have been carried out in the USA, Chile, China and Indea. After determining the work elements, continous time study method was used to develop wood hauling models for billet, pulpwoods and billet hauling with special equipment. Production in billet hauling was 2.135 m^3/h, billets hauling with special equipment 3.275 and pulpwood hauling 1.246 m^3/h, costs according to contarct were; 1.67 dollar/ m^3, 1.09 dollar/ m^3 and 3.58 dollar/ m^3. According to cutting permits 88.37% of industrial wood production was traditional processing products and 11.63% of industrial wood production was industrial logs.

Keywords: forest harvesting, animal logging, production, cost, wood hauling model, hauling time, hauling distance, load volume

1. INTRODUCTION

Animal Logging is a traditional forest harvesting system. There are 300 milion draught animals in the world such as oxens, horses, mules, elephants and Lamas (FAO, 1982). Information of the cost, productivity and products of any harvesting system will be helpful for logging planners. Such a information helps logging managers to improve the efficiency of the system, decision for changing or applying new machines and prediction of the workers and machines needed to harvest a distinict logging block . One of the usual method to measure production of harvesting machines or systems is time study which can be combined with cost calculation study and finaly the cost of unit work will be measured.
Mule skidding in Alabama was studied in pine and other broad leaves stand with slope 0 to 6% . The work team included 8 workers and 3 mules and production was 18.012 m^3/h (McGonagil, 1979).

Wang studied assessment of animal logging and ground skidding machines in Mountain region of Heilongjiang in China. Skidding distance was most important factor influencing skidding costs. The results indicated that the physical soil properties mostly depend on the amount of disturbance. The soil disturbance was higher in machine skidding (Wang, 1997).
Toms in Alabama studied animal logging as a small scale harvesting system . Minimum production was 2.45 m^3/h and best production was 25 m^3 per 8 hours with two teams and a person for cutting . The operators prefered area with slope of 0 to 30% because of low accident.

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 35-42.*

Mean daily production and payload were 16.095 and 0.212 m^3 . The cost of harvesting without the loading costs on trucks, was 49.31 $ per 2.36 m^3 . Mule logging was studied in the east of Alabama in the mixed stands, the results showed that damages to skid trails was low and approximately 2 inches of the soils was disturbed and some of trees were damaged. The most damages to the residual trees included broken branches by tree felling (Toms, 1996).
Residual stand damages in selective cutting by two skidding systems was studied in the Mssouri Ozark . The area of mule skid trails was 1% of the area of the logging unit, for the skidders was 4.6% (Ficklin et al, 1997).

In Chile wood extraction with oxen and agriculture tractors was studied by E. Rodriguez. The skidding distance was the only factor intered the skidding models developed for two classes of slope; -6 to –15 and –16 to –25 and for to classes of wood types; sawlogs and pulpwoods . Skidding distance differed from 20 to 240 meter (FAO, 1982).
The logging damages was studied by Ahmadi in the forests of Northern Iran (Lavidj , Amol), 27.1% of total damages to the stands was occurred by Mule Logging (Ahmadi, 1996).
The Mule Logging damages including damages to seedlings and standing trees was studied in Rouyan forests, 5.14 % of seedlings were grazed, 4.2 % of saplings were curved, 7.4% of the stems of the saplings were wounded and 4.2% of the seedlings and yearlings were destroyed. 5.1% of the samles had first grade wound, 8.29% second grade and 7.59% third grade (Tashakkori, 1996)

2. METHODS

2.1. Sites of study

The first site of study was 114 compartment of Patom district of Research and Training Forest Center of Nowshahr in the North of Iran .Table 1 shows the information of this parcel (Namiranian, 1997).

Table 1. Information of 114 parcel

Area(ha)	Min. height above sea level	Max. height above sea level	General slope(%)	Aspect	Geology	Soil	Forest type	Standing volume (sylve/ha)
38.4	650	750	35	North	Jurassic lime	brown	Fageto-carpinetum	360

The second site was 111 compartment located in Patom district.

Table 2. Information of 111 parcel

Area (ha)	Min. height above sea level	Max. height above sea level	General slope (%)	Aspect	Geology	Soil	Forest type	Standing volume (sylve/ha)
23.7	225	404	35	Northwest	Jurassic lime	brown	Carpinetum	339

The third site study was 218 compartment of Namkhaneh district.

Table 3. Information of 218 parcel

Area(ha)	Min. height above sea level	Max. height above sea level	General slope(%)	Aspect	Geology	Soil	Forest type	Standing volume (sylve/ha)
31.5	1100	1260	30	West	Paleozoic	Washed brown	Fageto-carpinetum	490.91

2.2 Climate of site study

There is no information of climate data in forestlands, but according to meterology station in Nowshahr, warmest month was July with average temperature about 24.6 $^{\circ C}$ and coldest month was February with average temperature about 7.5 $^{\circ C}$, most rainfall was 237.6 mm in October and lowest rainfall was 475 mm in June.

2.3 Data Collection

Continious time study method was used, work cycle included; loading the processing woods (billets and pulpwood) over mules, hauling the loads to landing, unloading and returning. Hauling distance, slope of skid trails and volume per load as important factors influencing hauling time, were measured. There were no technical and personal delays during this time study.

In order to determine the amount of the products of traditional processing method, the cutting permits of Patom and Namkhaneh districts from 1982 to 1996 were used.

In the northeren forests of Iran, the marking volume is determined from the tarif, after felling the marked trees, the forest service supervisors will measure the felled tree again, seprate the industial and nonindustial woods of each felled tree, then the contractors allow to process the felled trees to logs, lumbers, pulpwoods and the taditional products. Logs are defined as industrial woods and the lumbers, pulpwood and the other products defined as the traditional products in Iran. After processing the forest service supervisors will measure the products exactly, this stage is named as final measurement and the forest contractors should pay the rent of ownership based on the final measurement.

The percentage of each product for Fagus sp., Carpinus sp., Acer sp., Alnus sp. and the other species was calculated.

2.4 Statistical Analysis

2.4.1 Modeling

Model is a multiple regression to show the effects of variables on production amount (as function) . In this study, time of hauling by mule is a function of hauling distance, slope of skid trail and volume of the load. Using stepwise method, if the variable has a significant effect on RMS (residual mean squares) of model, it will be intered to the model, otherwise will not used. Because of saving time and cost, important factors including; hauling distance, skid trail slope and volume per load were measured, although the other factors such as experience of workers, power of mule, ground condition and temperature and… are influencing the time of hauling.

2.4.2. Production

Cost of Hauling System: Cost of system includes cost of purchase of animal, hauling instrument (straps, Pack-saddle, Sandal), maintenance of animals and labour costs . But in this study, cost of system achieved from animal conductor contract.

Number of Samples: By preliminary sampling and holding time accuracy about minimum hauling time, the number of samples was obtained according this formula:

$$N= (t^2 \times s^2) / E^2$$

Where, N: number of samples
t: from the student table
S: standard deviation
E: Accuracy

2.5 Work Organization

The work team includes a mule, a worker for loading with hand and a teamster . Sometimes, two or three mules may be connected by rope each others.
Two lumbers or two large pulpwoods (usually the weight per load is about 120 kg) are attached to the saddle of mule trough a plastic rope but for hauling the small fuelwoods, the workers use V-shap woody instrument.

Picture 1. Unloading the pulpwood at road side

Picture 2. Using V-Shape woody instrument to hauling fuelwoods

3. RESULTS

Hauling models for billets, hauling billets with special v shape woody instrument and pulpwood were developed by Statgeraph software.

a) Mathematical model for billets:
Y= 5.3366-0.001032×(X1×X2) + 0.014171× X1+0.079074×X2
df :29 R^2 : 0.850
Y: Time of each hauling cycle (min.)
X1: Hauling distance
X2: Slope of hauling trail(%)

b) Mathematical model for billets with V shape woody instrument:
Y= 0.310203×(X1×X2)
Y : Time of each hauling cycle (min.)
X1: Hauling distance (m)
X2: Volume per load (m^3)
c) Mathematical model for pulpwoods:
Y= 2.51553+ 0.235887×(X1×X2)
df:11 R^2 : 0.826
Y = Time of each hauling cycle (min.)
X1 : Hauling distance (m)
X2: Volume of load(m^3)

The validation of the models for billets and pulpwoods was tested, these models were acceptable at significant level of 0.05. Because of the few number cycles in hauling model for billets with V shape woody instrument, the validation test was not carried out.
In order two determine the effect of different variables on hauling time and hauling costs of three type load hauling each variable, was changed and the other variables were held constant . As hauling distance, slope of trails and load volume increase, the time and cost of mule hauling will increase too.
Production in billet hauling was 2.135 m^3/h, billets with special equipment 3.275, and pulpwood hauling 1.246 m^3/h . The hauling costs, according to contact, for billets was 1.67$/$m^3$, billets with special equipment 1.09 $/$m^3$, for pulpwood was 3.58 $/$m^3$.
The use of special woody instrument led to decrease hauling costs by 34.8%.

Table 1- Mean of the variables and working elements in Billet hauling

Distance(m)	Slope(%)	Load volume(m^3)	Loading time (min.)	Hauling time (min.)	Unloading time (min.)	Returning time (min.)	Total time (min.)
64.34	20.1	0.202	1.55	1.629	0.765	1.712	5.685

Table 2- Mean of the variables and working elements in Billet hauling with woody instrument

Distance(m)	Slope(%)	Load volume(m^3)	Loading time (min.)	Hauling time (min.)	Unloading time (min.)	Returning time (min.)	Total time (min.)
58.5	16.37	0.379	2.277	1.25	1.832	1.592	6.952

Table 3- Mean of the variables and working elements in pulpwood hauling

Distance(m)	Slope(%)	Load volume(m^3)	Loading time (min.)	Hauling time (min.)	Unloading time (min.)	Returning time (min.)	Total time (min.)
144.08	17.67	0.194	1.01	2.705	0.647	4.997	9.363

The calculations based on the cutting permits and final measurement of Patom district (area of 908 ha) and Namkhaneh district (area of 1084 ha) are summarized in the next tables.

Table 4- Percent of the products for Fagus sp. relative to final measurement

product	pulpwood	Lumber	Traditional and small lumbers
Percentage relative to final measurement	12.86	45.34	22.7

Table 5- Percent of the products for Carpinus sp. relative to final measurement

product	pulpwood	Lumber	Traditional and small lumbers
Percentage relative to final measurement	31.46	2.88	64.32

Table 6- Percent of the products for Acer sp. relative to final measurement

product	pulpwood	Lumber	Traditional and small lumbers
Percentage relative to final measurement	7.11	68.01	8.55

Table 7- Percent of the products for Alnus sp. relative to final measurement

product	pulpwood	Lumber	Traditional and small lumbers
Percentage relative to final measurement	8.79	64.36	0.39

Table 8- Percent of the products for the other species relative to final measurement

product	pulpwood	lumber	Traditional and small lumbers
Percentage relative to final measurement	26.07	47.34	21.78

In average for all the species, according to the results, 88.37% of the wood products are lumbers and traditional and small lumbers, only 11.63% are sawlogs.

4. CONCLUSION

Production-cost study of mule logging indicated that hauling time depends on hauling distance, slope of trail and load volume, amount of production is different in pulpwood and billets, cost of hauling will increase if hauling distance, slope of trail and volume of load increase. Because of a simple development by using V shape instrument to billet hauling cost, we propose that some skidding instruments should be used and studied.

The damages to soil and seedlings was studied in this area (Ghaffarian, 2003) too, the authors offered to plan skid trails carefully before logging to decrease site damages by mule logging, so it is necessary to note that haulimg cost will increase if hauling distance increase and logging planners should pay much attention to both site damages and hauling costs. In order to achieve costs of this system, another research plan should be carried out on prossecing cost of woods so that they have suitable weight and dimensions.

It is needed to carry out the research plans on the comparison of mechanized logging systems and animal logging systems based on economical and environmental issues.

Because of the huge amount of traditional wood products and low amount of sawlogs, we offered to extract the sawlogs as much as possible inorder to achieve more added value, prevent the wood wastage at the stump and decrease the satnd damages caused by mule logging.

5. SUMMARY

This study was carried out to measure cost production of mule logging and products of this traditional processing method. Using time study method, production of the mule logging was obtained, also the predicting hauling models for pulpwoods, billets and billets hauled by especial instrument were developed, skidding distance was a significant variable in the models and this is similar to the results of the other researchers as Wang (1997) and Rodriguez (1987), but the production rate is lower than the production of mule skidding in Alabama and the other places, it may be related to the different extracting method, because in Northeren forests of Iran, the pulpwoods or lumbers are hauled on the mules, so they are not skidded as animal skidding in the USA, China and the other countries. In slope area, heavy loads can not be hauled by mules and productivity is not so high. Therefore animal skidding equipment such as sledges, small sulkies or suitable saddles with chains adopted to the mules and forest condition of Iran should be made and tested on the operation.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Developing full-mechanized harvesting systems for broadleaved trees: a challenge to face the reduction of the manual workforce and to sustain the supply of hardwood industries*

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Abstract
The pool of the 4 forestry leaders in Europe (Germany, Finland, France and Sweden) totalises about 60% of the European wood growing stock and timber harvest: their total annual roundwood production is more than 180 million cubic meters. In Finland and Sweden, where 80% of the forest is composed of spruce and pine, close to 100% of the annual harvest are achieved by harvesters (Cut-To-Length system). In Germany and France, where the proportion of hardwoods in the growing stock is respectively 46% and 69%, the rate of mechanization is much more limited: respectively about 35% and 28%; the motor manual system (chainsaw + skidder/forwarder) is still dominating. However, full-mechanized solutions will be needed for broadleaved stands. Indeed, as it has been clearly demonstrated in France, while the number of new entrants in the logging business does not stop decreasing, mechanization is the only solution to sustain the supply of raw material to wood industries. However, taking into consideration the feed-back from loggers, the CTL machinery (harvesters) currently on the market, initially purposed-built for cutting and processing conifers, seem not to be adapted for processing all types of trees, especially broadleaved trees of temperate forests (oak, beech, chestnut…) characterized by an irregular shape, a wide crown and large branches. Besides, the economical feasibility of North-American systems combining at least 3 machines (ex: feller-buncher + skidder + processor) is not proved in small-sized logging sites (a few hectares only) as it can be common in many parts of Europe. Several other alternatives are currently experimented, especially in France, to find cost effective solution to harvest hardwoods with machines.

1. INTRODUCTION

All over Europe, mechanization of logging operations has expanded during the 3 last decades, and still expands, in the Western and Central Europe countries (UK, Norway, Germany, France…) but also, recently, in the Eastern countries such as Poland. Thus, in Finland and Sweden, close to 100% of the annual harvest are achieved by harvesters (Cut-To-Length system). In Germany and France, the rate of mechanization is much more limited: respectively about 35% and 28%; the motor manual system (chainsaw + skidder/forwarder) still dominates.

Meanwhile, in many countries, jobs in logging business are less and less attractive and the number of new entrants in this sector does not stop decreasing. An enhancement of

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 43-53.*

mechanization, especially in hardwoods, is needed to ensure the supply of raw material to wood industries. But are the CTL machinery (harvesters) developed for conifers suitable also for harvesting all kinds of broadleaved trees, especially those of temperate forests (oak, beech, chestnut…), with irregular shape, wide crowns and large branches?

To face this challenge, several experiments of mechanization in hardwoods are currently ongoing, particularly in France. This paper aims at presenting more in details the stakes of mechanization as well as presenting the state of the art regarding experiences of hardwood mechanization, with a special attention to the French situation.

2. WORK FORCE AND MECHANIZATION: THE STAKES SEEN FROM THE FRENCH POINT OF VIEW

2.1 Harvested volumes: facts and perspectives

In Europe, the pool of the 4 forestry leaders (Germany, Finland, France and Sweden) totalises about 60% of the European wood growing stock and timber harvest: their total annual roundwood production is more than 180 million cubic meters. But when in the two Nordic countries, 80% of the forest is composed of spruce and pine, the proportion of hardwoods in the growing stock in Germany and France is respectively 46% and 69%.

In France the biological forest growth (top end diameter of 7cm) is close to 92 million cubic meters per year. The annual marketed harvest of roundwood has been quite stable for several years, around 35-37 million cubic meters. Besides, about 24 million cubic meters are also harvested by individuals as firewood for self-consumption. So, there is a big potential for harvesting more wood every year, which is of particular interest considering the current increasing international demand of wood.

The new French Forest Policy elaborated in the last two years takes these facts into account: the objective is to develop the economy of the forest wood based industry through harvesting more wood in the French forest. It is expected that the increase of the harvest will be concentrated on softwood timber (time to harvest has come for pine, spruce and Douglas fir plantations resulting from the large campaign of reforestation that took place after the second world war, and European softwood sawmills production is expanding) as well as on fuelwood (to sustain the supply of energy plants that are to be installed in the short and medium term according to the national plan for increasing the level of production of renewable energy). This fuelwood should be found in logging residues (softwoods + hardwoods) but also in poor quality stands (mainly hardwoods).

Table1. Expected evolution of wood market in France. (Laurier, 2006).

	Marketed harvest in France (Million cubic meter)			
	2004	**2005**	**2010 (*Estimation)***	**Variation 2010 / 2005**
Softwood roundwood	22	22,6	25	+2,4
Hardwood roundwood (including firewood)	13,2 (2,2)	14,4 (3)	15 (3,5)	+0,6
Chips for energy	0,2	0,5	2,5	+2
TOTAL	35,4	37,5	42,5	+5

Harvesting more wood means a need of extra machinery and workforce. But, right now and for several years already, both loggers and forestry schools do not stop complaining about the difficulties in recruiting motivated candidates.

2.2 Forest workforce evolution and its consequence on mechanization development in France: facts and prospective

Official statistics concerning the population of loggers are quite scarce, and focus on wage-earners only. To approach the whole population of loggers (including self-employed people and contractors), it is necessary to cross-check different sources of data (numbers of logging companies, of wage-earners, of machines, average productivities…) and to consolidate regional and national analysis. According to this system of calculation, the total number of people working in the logging business in France (excluding office jobs and people in charge of wood trade only) would be approximately 14 600 whom 11 000 chain saw operators (Laurier, 2005).

Cf. figure 1 & 2.

Figure 1. Loggers population in France (managers + wage-earners) in 2004.

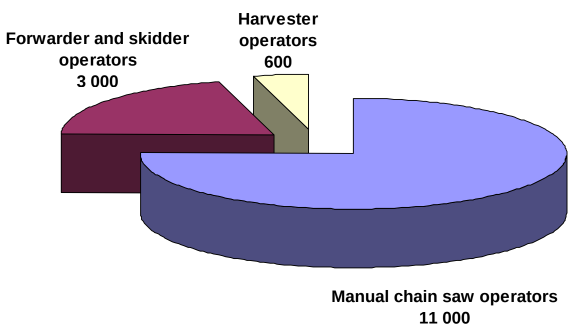
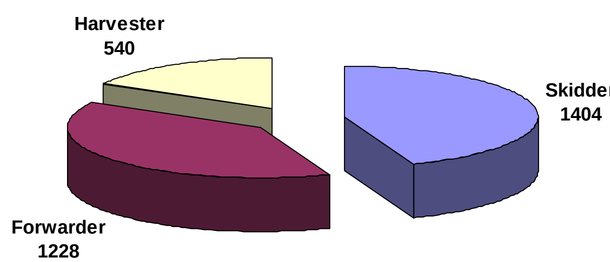


Figure 2. Forest machines fleet in France in 2004.



Laurier showed that the population of loggers considerably decreased for the last 25 years: it has been divided per 3 while the national annual harvest has been multiplied by 1.3 along the same period (figure 3). This was possible thanks to mechanization, initially developed in the first thinnings in softwoods (end of the eighties), but which came to second and third thinnings and finally to final cuts (figure 4). The Cut-To-Length system combining harvesters and forwarders has been more and more taking over from the "traditional system", where trees were cut and trimmed by motor manual operators and extracted in full length by cable skidders. In the European project ERGOWOOD, Le-Net *et al.* (2005) clearly demonstrated that in France, the development of mechanization has been a "follower phenomena", that is to say a consequence of different driving forces, among which the increasing difficulties for loggers to find qualified chainsaw operators. The hardness of the job as well as the little attraction for manual jobs in general in the current French society, are the main reasons explaining the lack of new comers in this business.

Figure 3. Number of wage-loggers and annual marketed harvest from 1978 to 2004 in France.

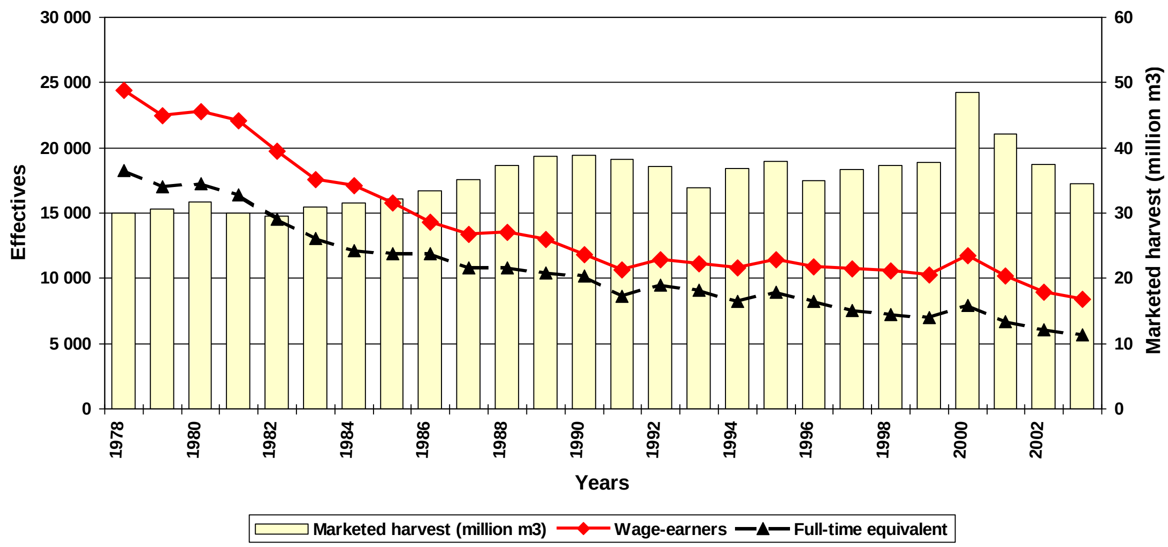
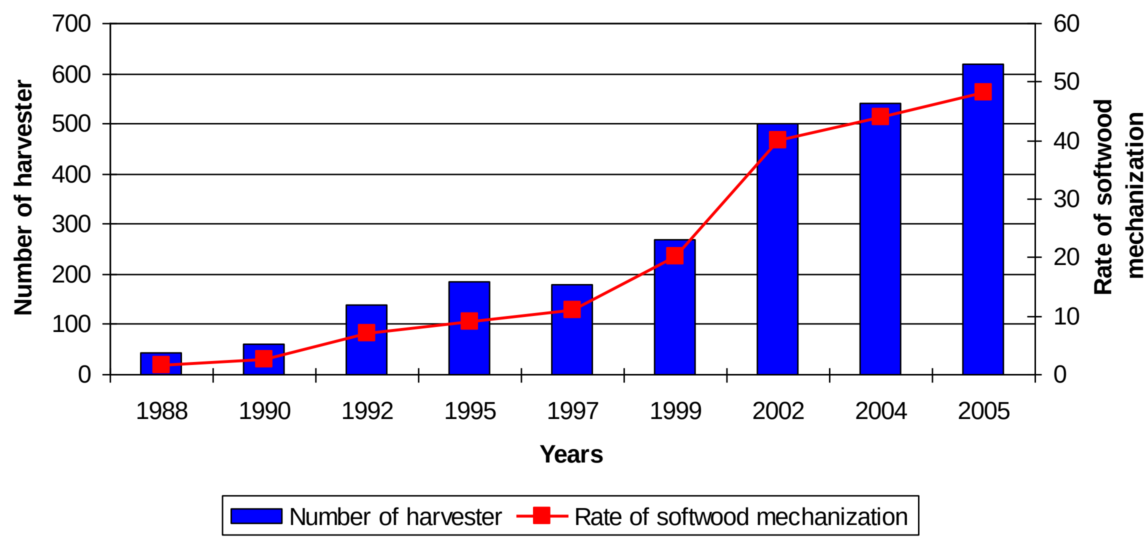


Figure 4. Evolution of the mechanization rate in softwood harvest in France.



3. SURVEY OF THE CURRENT HARDWOOD MECHANIZATION

3.1 A few examples of hardwood mechanization in Europe

In Northern Europe (Sweden, Finland, Norway, Denmark), forests are mainly composed of coniferous species, with 80% of spruce and pine. There are broadleaved species (birch, aspen…), but quite easily processed with conventional single-grip harvesting heads as trees in these boreal or sub-boreal forests look like conifers: they are relatively straight and have little branches.

In Spain, 300 harvesters work in pine stands or in eucalyptus stands. The 225-240 harvesters working in eucalyptus are mostly CTL harvesting heads mounted on tracked excavators.

In Germany, 90% of the broadleaved stands are high forests, and the number of stems kept per hectare is quite important. So trees can be cut and processed without too many difficulties by conventional harvesters. The rate of mechanization would be about 20% (close to 2 Mm^3 per year) in German hardwoods, with some variations between Länders. Due to the lack of manual workforce and storm damages in the nineties, mechanization is more developed in West Germany.

Picture 1. Straight stems, few and little branches: these German trees can be quite easily cut and processed by conventional single-grip harvesters

3.2 Hardwood mechanization in France

Hardwood mechanization really started in France at the end of the nineties and in 2000, just after the 2 large windstorms. There, the work was so dangerous for chainsaw operators that hardwood mechanization seemed to be a good solution. But, according to the results of the 2 national surveys carried out by AFOCEL (Bigot & Cuchet, 2003; Cacot & al., 2006), the situation did not really evolve between 2002 and 2005: the rate of mechanization remains about 2-3% of the annual hardwood harvest (350 000 m^3 on a total of about 13-14 million cubic meters). There are 50 harvesters of various trademarks common used for softwood harvesting operating in hardwoods (but 30 full-time equivalent harvesters). They belong to 45 logging companies; 30 of these were of the pioneers. Most of them are located in Middle-West France (Limousin, Poitou-Charente, Dordogne), where the rate of mechanization is up to 15% (chestnut coppices mainly).

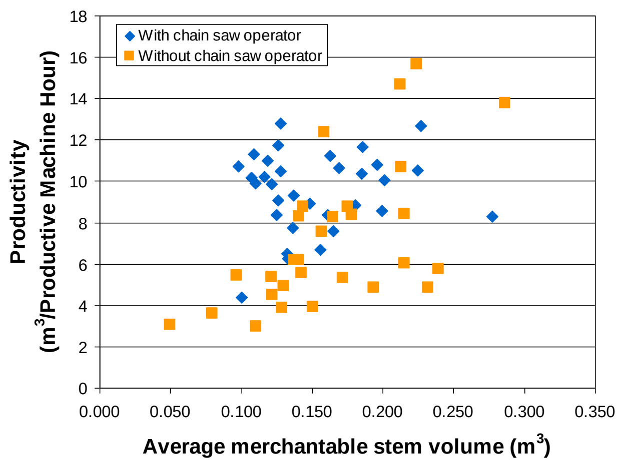
Loggers operate according to various systems of organization but also in different conditions. For example:

- If most of the harvesters work alone, some loggers employ a chain saw operator to cut the too big trees and the non-merchantable stems, and if necessary to re-cuts the stumps and check/correct quality and grading of the logs bucked by the machine, in order to improve the quality and the productivity of its work. Nevertheless, with the higher and higher lack of chainsaw operators, this system is less and less used;

- Some loggers are specialized in the value recovery of small and medium sized trees, processing up to 8 different kinds of logs per logging site, others concentrate on pulplogs production.

As a result, the hourly productivity is very variable (figure 5) as well as the annual production: from 7 000 to 15 000 m^3/year/harvester, for a machine operated in a single shift, full-time in hardwoods. With an average daily productivity of around 50-60 m^3 and prices between 8 and 15 €/ harvested m^3, the daily turnover varies from 400 to 900 €, while the daily costs of the machine can reach 800 €. Such conditions are economically hard for loggers.

Figure 5. Example of harvester productivities in clear cuts of chestnut coppices in France.



3.3 Limits of hardwood mechanization with the current harvesting heads

Loggers operating harvesters in hardwoods use 3 kinds of harvesting heads (Bigot and Cuchet, 2003):

a) Conventional single-grip softwood heads without modification, except the adjustment of knives pressure, rolls speed…
b) "Hardwood" heads as their manufacturers call them, but that are conventional softwood heads on which special modifications have been made (addition of a top saw, adaptation of the number and the shape of the knives…),
c) Purpose built harvesting heads, specifically designed for hardwoods.

In the category c, there is just one model (Charlier CA 562HW, existing in 2 exemplars), operating only in chestnut coppices until now. From a technical point of view, this equipment proved itself but the economic feasibility has not been demonstrated yet in such stands. As far as the category b is concerned, loggers did not rush on the so-called "hardwood" heads proposed by the manufacturers: they preferred to develop their own technical solution from conventional heads of the category a (KETO 150, AFM 60, TJ 746 & 742...). These individual solutions are appropriate to the type of logging operation (thinning or clear cut) and broadleaved stands they have been developed for. But, they quickly reach their technical and economic limits in other types of broadleaved stands and/or operation, especially as soon as the trees look like less to coniferous. Harvesting heads are then subjected to hard working conditions, particularly during the delimbing process (strikes against the big branches). Consequently, costs and time dedicated to maintenance and repairs are very important.

Besides, North-American systems combining at least 3 machines (ex: feller-buncher + skidder + processor) are not attractive to European loggers because of the small-size of logging sites (a few hectares only), common in many parts of Europe. The small size of logging operations compromises very much the economic feasibility.

Despite the lack of motor-manual workforce, especially for processing pulp logs in small sized hardwoods, we can expect that loggers will not come more to hardwood mechanization until manufacturers will not propose real adapted solutions. Loggers as well as wood supplying companies belonging to pulp & paper groups think there is no efficient and cost effective solutions yet for harvesting hardwoods with machines. Several of these professionals then, with the support of public funds, AFOCEL and/or some manufacturers, experiment alternatives.

4. EXPERIMENTS OF ALTERNATIVE TECHNIQUES IN PROGRESS

As there is a large diversity among broadleaved stands, there should be the place for different technical solutions. For each major kind of stand found in France, AFOCEL analyzed the specific constraints and experimented techniques that seemed *a priori* adapted (see table 2).

Table 2. Techniques experimented for different types of broadleaved stands found in France, taking the specific constraints of the stands into account.

Logging operations	**A - Clear cuts or thinnings in coppices**	**B - Thinnings in high forests**	**C - Clear cuts or thinnings in a mix coppice / high forest**
Main species	Oak, hornbeam, chestnut, beech	Oak, beech, birch, sycamore tree, ash…	Same species than for A and B.
Main constraints	- Volume of the average stem can be very small (<0,2m^3). - Reaching and cutting stems in a clump can be difficult. (Picture 2).	- Special attention is needed to avoid damaging the remaining trees. - In the youngest stands, volume of the average stem can be very small (<0,2m^3). - In older stands, forks and big branches in large trees are hard working conditions for the harvesting head. (Picture 3).	Great variability of the diameters An addition of the constraints of A (coppice) and B (large trees).
Technical solution experimented or close to be experimented	- Separation of felling and processing ① - Integrated solution for both pulpwood and energy wood ② - Multi-stem harvesting head ③	- In young stands: see case A (① ② ③) - In older stands: a specific har-vesting head for large trees ④	- techniques of case A (① ② ③) for coppice - a special processing head to buck logs in the crowns of the large trees ⑤

Pictures 2 and 3. Numerous stems per clump and big branches are not favourable to mechanization.

The results or, at least, the work in progress for the different technical solutions are successively presented for the 2 types of trees the most challenging for mechanization:

- small sized trees (stem volume under 0,2 m^3). With trees of such a size, the low productivity is very compromising. Moreover, trees may be difficult to reach and cut if they are grouped into clumps (coppices); *Cf*. Picture 2.
- large sized trees (between 0,4m^3 and 1,2m^3). Big branches and forks are unfavorable to an efficient trimming (*Cf.* Picture 3). Besides, crowns of large trees are a non negligeable source of pulp logs in France but the productivity of the harvester when bucking logs in the crown is quite low.

4.1 Solutions for small sized-trees

Being the first field deserted by chainsaw operators, it is the one for which experiments are the most numerous. We present here the full-mechanized technical solutions only.

Separation of felling and processing - Solution ①

A 2 machine-system has been experimented for nearly 2 years by one of the most important wood suppliers of the International Paper French pulpmill in Saillat. Before, this logger used to work for 4 years in chestnut and oak coppices with 2 conventional harvesters but he was not satisfied with the results: average productivity was about 5-6 m^3/machine hour only. So he kept one of its conventional harvester equipped with a Keto head specially modified for hardwoods (KETO 150) to trim and buck the trees, and he invested in a Naarva grip 1500-40 to take in charge the felling of the trees.

The Naarva head is a guillotine with a cutting capacity of 32 cm initially developed in Finland for energy wood. The results of such a system were encouraging: the average productivity of the processing machine raised to 10,2 m^3/hour. Unfortunately, after 6 months of working in hardwoods, the Naarva head was almost destroyed, not strong enough despite changes in the cutting system. A few months ago, it has been replaced by a heavy duty QUADCO feller-buncher equipped with a shear of a cutting capacity of 58 cm. This is the first machine of this type in France.

Pictures 4 and 5. The Naarva guillotine and the Quadco shear tested in chestnut and oak coppices.

This solution will be studied as soon as the training period of the operator is completed, regarding work organisation (task allocation between the 2 machines), productivity and cost but also:

- the ability of the shear attachment to fell stems in dense clumps, with a good quality of the cutting (no damage on the stump, cutting as close to the ground as possible) in order to allow a new generation of the coppice,
- the minimum size of the logging site for absorbing the cost of the transfer of 2 machines instead of 1.

Integrated solution for both pulpwood and energy wood - Solution ②

Recently, some manufacturers have developed small-sized feller-bunchers, particularly adapted for harvesting small trees. One of these machines – Timberjack's Energy Harvester, equipped with a felling head and an accumulating arm – has been tested in the European project Forenergy1 on 3 of the most promising resources of small trees in Europe: Finnish young conifer forests, French coppices (hornbeam, oak) and Italian single-row plantations of black locust. The average productivity recorded was between 4 and 8 green tonnes per net working hour. Best results (8 tonnes) were obtained in single-row plantations, where the machine can manoeuvre with ease and has only to fell and bunch the trees (that will be chipped in a further step). Worse

[1] Project NNE5-2000-00395 "FORENERGY". Budget: 4,6 M€. With the participation of 9 partners from Austria, Finland, France, Italy, Sweden and United Kingdom. Tests conducted by R. Spinelli, E. Cuchet and P. Roux.

results were found in thinnings of coppices, where the machine was in charge of both felling the trees and cutting pulp logs in suitable stems. Moreover, in this type of operation, the constricted work space limits the degree of freedom to approach the target stems, so the head has to manoeuvre before getting the right position to fell the stem.

This project finished 3 years ago, and no such a machine has been sold by the manufacturer in France. Like the Naarva, this head specially built for felling energy wood is not strong and productive enough to also cut pulp logs or small diameter sawlogs in French broadleaved stands on a full-time basis.

Multi-stem head – Solution ③

Tests on another and stronger multi-stem head (a Logmax 4000 mounted on a TJ 1070) are programmed in the coming months, as part of a 3-year research program launched in 2006 by several pulpmills using hardwoods in France and belonging to the pulp & paper groups Saïca, Burgo, Tembec and International Paper companies.

4.2 Solutions for large sized trees

Until now, solutions for large broadleaved trees have not been investigated much.

A specific head to process the crowns of the trees – Solution ⑤

In 2002, AFOCEL tested in forest conditions 2 grapple-saw initially designed for a use on wood yards but reputed for their ability to process twisted stems without having to drop them, thanks to special rolls: the HUET grapple (Belgium manufacturer) and a prototype of the Swiss company AFICOR. This was done with partners from the pulp and paper industry and contractors. The tests have been carried out on 4 logging sites with beech and oak crowns (roughly cut by the chainsaw operator who prepared the large pieces of timber in the main stem). The Huet grapple (1800 kg) was mounted on an excavator while the AFICOR (750 kg only) was mounted on a forwarder base and could cut the logs directly into the berces. The productivities observed in the forest were between 15 to 20 m^3/hour, while about 30 m^3/hour on wood yards of mills. But, above all, these grapples revealed too much fragile in forest conditions, particularly the AFICOR one with the hydraulic hoses. Hence this solution has been abandoned.

A special head to process large trees on a whole – Solution ④

One of the target of the on-going European project "forstINNO", leaded by the German manufacturer HSM and in which AFOCEL takes part, is to build a single-grip harvesting head able to take a maximum of the value of the wood from trees between 0,4 and 1,2m3, both in the main stem and in the largest branches of the crown (diameter > 10cm). This is a very challenging target for 2008.

5. CONCLUSION & PERSPECTIVES

In the medium term, shortage of chainsaw operators in hardwoods in France could become a real bottleneck for the supply of raw material to hardwood industry, especially to pulp mills and sawmills specialized in small logs. A realistic hypothesis is that 30% of the hardwood harvest (which is of 14 million cubic meters) should be mechanized in the middle term in order to counteract the lack of motor-manual workforce. This rate of mechanization may be reached with about 300 machines, in broadleaved stands on favorable terrain conditions and with trees not too much branched or twisted (poplar plantations, young high forests, coppices).

However, the fleet in hardwoods has been remaining for several years around 30 full-time equivalent harvesters only. Current technical solutions proposed by manufacturers are not cost effective in too many types of broadleaved stands commonly found in France. Loggers are in expectation for alternatives: it is up to the researchers and forest machine manufacturers to find real innovations, satisfying from both a technical and economic point of view.

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Standardizing on Forest Operation System and the Accurate Estimation by System Dynamics*

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Abstract

In order to keep forest operation under environmental tolerance and to have accurate estimation on the operational efficiency, a flexible model is inevitable and the system control is also expected to be discussible on it System Dynamics, SD, represented the model and showed which was useful, which was based on Flow, Storage and control/interaction among them and the other value/events. The modeling method provided a standardizing for kinds of forest operation systems at various site conditions. This flexibility is the major merit of the modeling method to utilize at difficult terrains. Expects of system operation output had reliable accuracy. Control and maneuver on the system were discussible as well, and the environmental and productive feedbacks were also adoptive and numerically suggestive.

1. INTRODUCTION

Log harvesting operations were conducted by various ways the place with complicated landform and different road basis service degree. As for the way of work's there being, each of the scenes were various and to be standardized even if it was possible to divide them roughly according to the method into the cable system or the vehicle system, it was difficult to estimate productivity. Also, the productivity of the individual work is statistically estimated from the business result but it was not easy to improve estimate precision because the condition of each operation field is often different. It tried to estimate work efficiency by modeling log production operation system with the System Dynamics method in this research through presenting the work itself on the computer. Moreover, it made it possible to review improvement about the element work and the link which forms the balance of each process quantitatively.

2. THE MODELING OF A SYSTEM DYNAMICS AND A TIMBER PRODUCTION OPERATION SYSTEM

The System Dynamics is the model representation to show how the factor which composes a system. It influenced the flow, putting a change with two pieces of quantity and flow among them quantitatively in the whole system causality. The flow, the stock and the valve which becomes a main element when composing a model are shown in figure 1. As for the flow, the quantity (number of the felled tree and so on) which occurs with the other component is the continuation of the process and the one (the felling and so on) which controls it is equivalent to

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 55-61.*

the valve. The flow is stored up at the stock (all the trees which lay on the forest ground and so on) (1). The model to show timber production operation by this is shown in figure 2. This modeled to introduce a processor into the tree processing process of the operation system; the organization of the system consists of operation road opening by an excavator, manual felling, and tree hauling by a small grapple crane, tree processing and the forwarder log transportation to pile up them at road side landing. It separates into the timber production process at lower section from the road opening process in the upper section on the figure 2. Also, it gives value such as the size and the standing tree density of the operation block which is necessary to set the site condition to the entry format table by the condition setting parameter as shown in figure 3.

It shows the process that box b1 in the figure 2 upper section opening up road for operation. It makes extend from until the road reduces the maximum reach distance in the object forest block to the goal value. It sets a goal value and establishment work efficiency with maximum reaching distance to the concerned parameter in the entry table of figure 3. The state of the progress of the concerned process is shown in figure 4. It achieves the goal on the 10th day and which shows that the whole area became accessible at equal to or less than 80 m of the maximum reach distance. Box b2 shows manual chain saw felling work. The number of felling tree is calculated from the size of the cutting block, the standing tree density and the thinning intensity and the process is conducted by the felling efficiency. The actual felling work was done by line thinning method and the number of feller was three. The number of feller was set as a parameter. Felling work wasn't done simultaneously with road opening work considering on the safety and their interference.

It decided to begin felling work if the opening road work moved ahead by 200 m. The actual work was conducted as same way.

Box b3 shows the process of full tree hauling from in-stands to road side. The work draws out felled tree from on the felled line in-stand to the road side by a small grapple crane. It advances to the next felled line after one line have finished. Operational efficiency to finish a line was set to the parameter. However, when the amount of the one day felling process doesn't fill one day ability of the post process, it doesn't work the day. That is, a process is always designed to operate without dull condition.

Box b4 shows timber processing process. In the actual work, it was done by manual work but the model was improved to utilize a timber processor to the process to discuss on the operational efficiency by that. Because the processing contents are same, the structure of the model doesn't change. However, so as not to make the machine play occur like the tree hauling at the preceding process, it judges whether to work or not to evaluating the rest amount of the precedent process and the work efficiency. The model this time set equally three logs are produced from one tree when a full tree is processed.

Box b5 shows log forwarding process. It carries out the logs, which were bunched onto the operation road side in the woods, to transport by the forwarder to the beginning of the operation road at the forest road side to pile them up. It works when there is more amount of one day work than the precedent process so as not to make play occur. It sets work efficiency in the entry in the site condition setting table as the parameter. The process of this box differs to the other precedent ones, because the precedents handle "the tree" before it is processed. This process offers a processing process which changes flow quality from tree to log and also the quantity depends on this process. In the System Dynamics which models flow with quantity, the operation system becomes the expression to handle ones with different quality even if it cooperates in process. As for the processing process, generally, the number of logs differs in each tree due to the quality of the individual trees such as the curve and the decaying. It is efficient to estimate the number of logs which can be obtained from single tree after judging of the quality. It is inevitable to give the parameter value of the model seem to be valid.

The various operation systems can be composed by the sub model of the process which depends on such System Dynamics structure and even if it supposes that it was a complicated structure, they can be expressed by it being standardized form.

3. THE ESTIMATE AND THE APPLICATION OF THE TIMBER PRODUCTION OPERATION SYSTEM

The state of the work progress when introducing a processor into the processing process of the timber harvesting operation is shown in figure 5. The operation simulation result showed pile amount, fw, did not increase after 51st day from the beginning of road opening, fl, to finish the harvesting operation. Tree hauling process, hl, and timber processing process, pr, cooperated with the work at the precedent process. In case of actual operation (2), the number of the operation days was same approximately. As for the model which processes timber by manual work, it showed 6.7m^3/the man-day for the productivity and it was about 7 m^3/the man-day by the model. It revealed reliability for the estimation. When applying a processor, it was estimated that it became the productivity of 10m^3/the man-day through total process. It was expected that the operational productivity will be improved by about 1.5 times by introducing the processor.

4. SYSTEM PRODUCTIVITY ESTIMATION

It is possible to make a table as shown in the figure 6 that the productivity of the whole timber production operation system and the partial process can be glanced when assembling and showing the work productivity on the same figure. These changes dynamically with the condition of the system and also is able to estimate the system productivity correctly. This is named System Productivity Estimation. The effect of the improvement of the process which composes a work system can be quantitatively evaluated easily. Moreover, it seems to be valid and useful when the terrain is difficult and complicated in operation condition just like as that in Japan.

5. CONCLUSION

The modeling of an operation system by the System Dynamics made good estimation with high precision. However, it needs favorable tuning on the model with highly accurate relationship between processes which enables by simulation to reproduce operation advancing and production accurately. Also, at present, it makes display a table at the same time as much as the work condition table, the progress graph, the success of the work on the one screen of PC like figure 7 and it makes it easy to grasp a change as much as the success by the work condition.

When making a system as the package software, the design of the interface to enable mutual reviewing on operation system for the reviewing manager seems to be important.

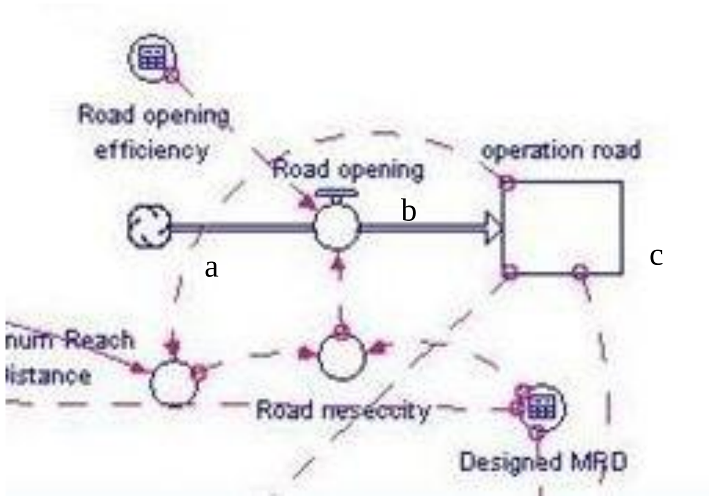


Figure 1. The main component of Sytem Dynamics model.
(a): flow, (b): valve and (c): stock

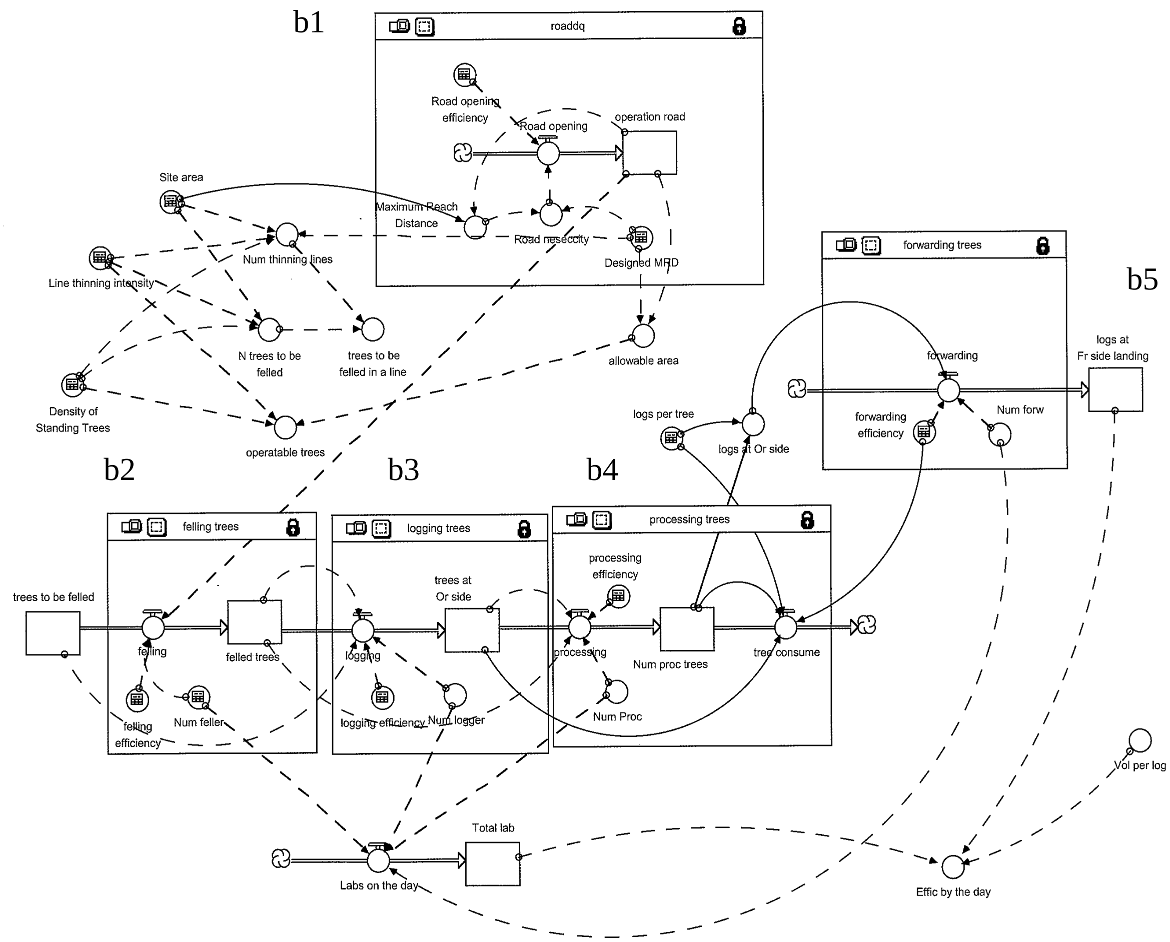


Figure 2. The System Dynamic model of timber harvesting system.

Site condition		
Site area	(ha)	8
Density of Standing Trees	(n/ha)	1200
Line thinning intensity		0.3
Designed MRD	(m)	60
Num feller	(man)	3
logging efficiency	(n/day)	120
felling efficiency	(n/day)	60
forwarding efficiency	(log/day)	240
processing efficiency	(tree/day)	360
Road opening efficiency	(m/day)	60
logs per tree		3

Figure 3. Table to set values for site conditions.

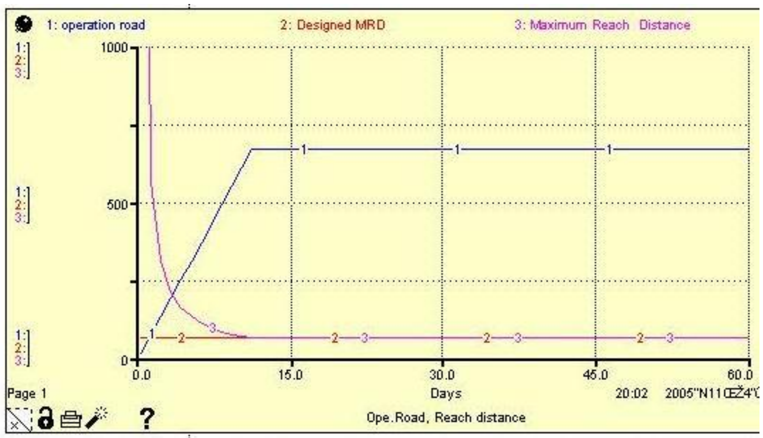


Figure 4. 'Progress of operation road opening.

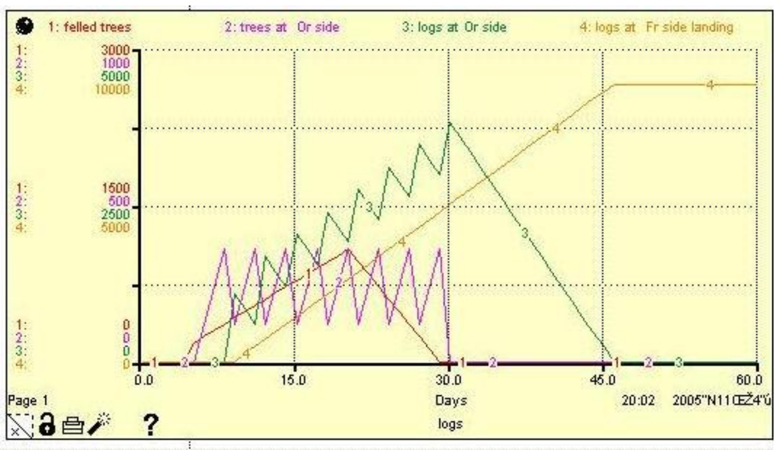
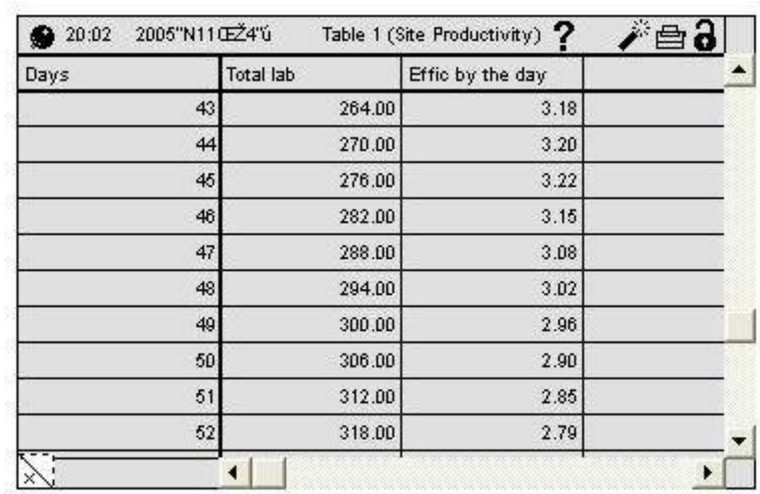


Figure 5. Progress of timber harvesting operation .



20:02 2005"N11ŒŽ4'ú Table 1 (Site Productivity)

Days	Total lab	Effic by the day
43	264.00	3.18
44	270.00	3.20
45	276.00	3.22
46	282.00	3.15
47	288.00	3.08
48	294.00	3.02
49	300.00	2.96
50	306.00	2.90
51	312.00	2.85
52	318.00	2.79

Figure 6. System Productivity Estimation.

The left end column is the number of the work days and the center is done the production m3 of the whole work squad., the right end is productivity m3/a man-day.

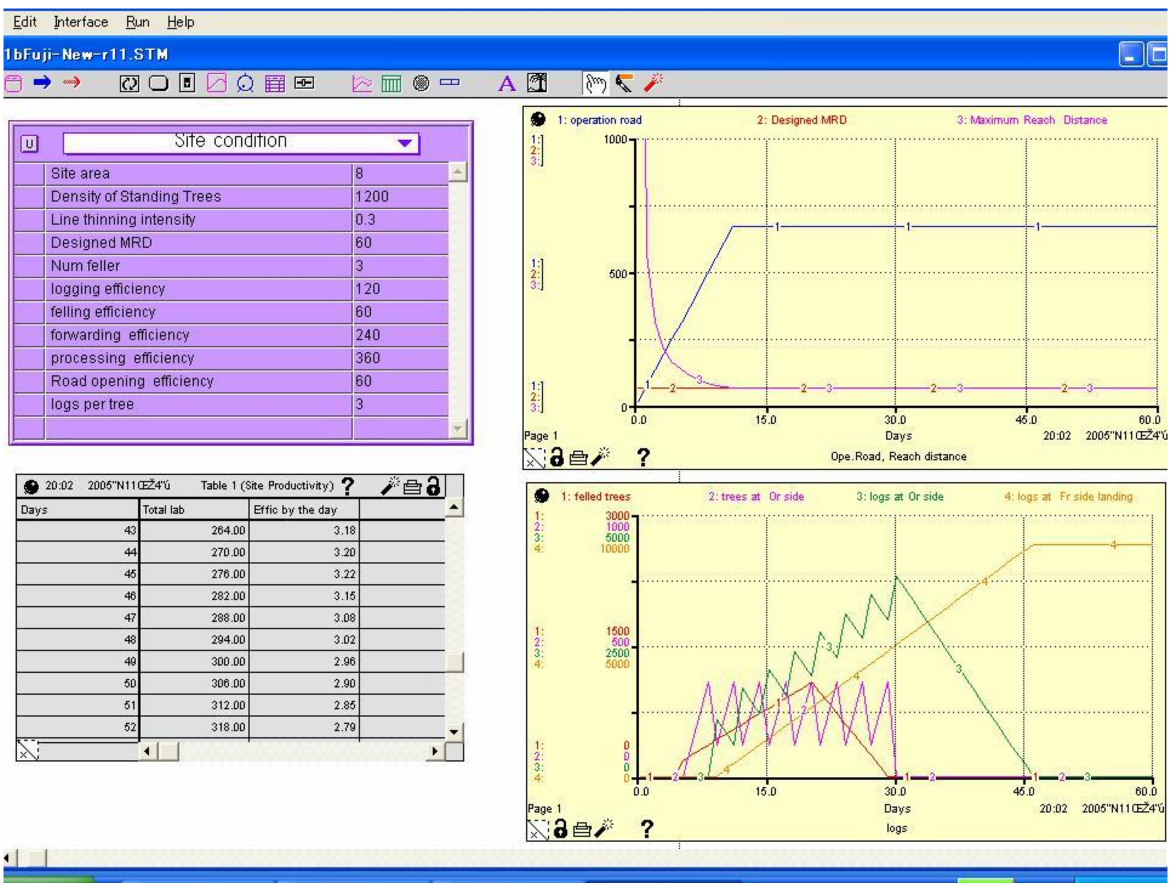


Figure 7. A display of multi-output for interactive reviewing.

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A Timber Harvesting Decision Framework for Ethiopian Forests*

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Abstract
Ethiopian forests provide significant benefits to the 73 million Ethiopians through environmental protection and as a valuable, widely used resource base. Current use and demand for fuel wood and lumber exceeds the local forest capabilities and the industrial capacity to process and deliver lumber to the market. Intense demand for forest products has lead to overexploitation of the existing forests, imported wood from abroad, and the substitution of other products to meet these needs. Unsustainable forest utilization for lumber production is one area that could be improved in order to help decrease impacts on Ethiopian forests. Forest harvesting is one of the first and most visible steps in the lumber production process where sustainability improvements could provide more economic returns, decrease environmental impacts, and enhance socially responsibility. An investigation to identify the critical decision and issues facing forest managers in forest operations was completed using social science research methods combining aspects of ethnographic, grounded, and participatory research theories. Complied decisions and issues were then organized into a structured decision framework that can be used by land managers to implement improved harvesting approaches. The framework is based on basic concepts of decision support and draws upon multi-criteria decision making and prioritization techniques to facilitate the development of meaningful solutions that are possible to implement. This paper presents the theory and process used to develop the decision framework in the context of forest operations in Ethiopia. While sites in Ethiopia were used to develop this framework, many parts of the developing world face similar questions and situations that fall into the same decision making categories. The adaptation of this process for decision framework development outside of Ethiopia is possible with only minimal adjustments for local conditions.

1. INTRODUCTION

Ethiopian forests provide significant benefits to the people of Ethiopia through environmental protection and as a valuable, widely utilized resource. Rural villagers often rely on forests for sustenance, fuel, shelter, livestock grazing, non-timber forest products, while urban Ethiopians depend on forests for building and construction materials, furniture, handicraft supplies, and other products. Unfortunately, the current use and demand for wood exceeds the local forest capabilities and industrial capacity to process and deliver these products to the market. This disparity between natural and industrial production and demand results in the overexploitation of the existing forests, imports from abroad, and the substitution of other products to meet these needs. Both unsustainable forest utilization and substitution help perpetuate the cycle of poverty, food insecurity, and natural resource degradation. (EFAP 1994)

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 63-70.*

With a one of the largest population in Africa at over 73 million people and growing at 2.36% a year (CIA 2005) the demand for forest products and land uses that are not congruous with forestry will only increase in the coming years. As the formal forest industry in Ethiopia is very small in size and output, very little development and government emphasis is placed on the forest industry. The historic trends of poor funding, little concern for updating current policies, and removing barriers to new investments and development of the industry are currently being maintained or worsened. A strong, sustainable forest industry can help provide the raw materials that feed growing economies and assist in rural development throughout the country. Annual industrial wood production in 1994 was estimated at 150,000 to 2000,000 cubic meters which was only half of the domestic demand for wood. (EFAP 1994) While good estimates of the current overall production are lacking, many mills in the natural forest have shut down and mills working with plantation wood have maintained or slightly increased their production while demand has continued to grow. Improvements to the harvesting, transportation, and other log supply process components can provide the raw material necessary to open the existing mills and promote new investments to fill the gap between local supply and demand.

An investigation to identify the critical decision and issues facing forest managers in forest operations was completed in order to build a decision framework that can be used to improve the sustainability of forest operations. Social science research methods combining aspects of ethnographic, grounded, and participatory research theories were used to populate the concepts that create the decision framework. The framework itself is based on the basic concepts of decision support and draws upon multi-criteria decision making (MCDM) and prioritization techniques to identify meaningful solutions that are possible to implement. This paper presents the theory and process used to develop the decision framework in the context of forest operations in Ethiopia.

2. SITE DESCRIPTION

Three sites were identified for investigation in this project. One natural forest site was used for natural forest logging data collection and two plantation forest sites were used for production forest harvesting data.

2.1 Natural Forest

Harvesting and sawmilling sites in southwestern Ethiopia's natural forest areas near the towns of Meti and Tepi (
Figure 1) were selected for this project to illustrate current approaches to natural forest timber harvesting. This area has common tropial natural forest harvesting conditions with widely scattered large diameter indigenous trees. The commercial trees often occur in low densities of less than five trees per hectare. The species found here include *adolfi-fiederici, Croton machrostachyus, Olea species, Cordia abyssinica,* and *Hagenia abyssinica* and many others. While over 300 species have been identified in these forests, only 25 were utilized commercially. Another 30 have commercial potential, although many of these species like *Cordia Africana, Juniperus procera, Podocarpus falcatus, and Hagenia abyssinica* have been declared "protected" by the federal government and are illegal to harvest.

Figure 1. Research site locations

The state owned Sawmill and Joinery Enterprise (SJE), headquartered in Addis Ababa is the primary enterprise responsible for the milling and production wood products from the natural forest. They own and operate over 22 sawmills and joinery factories throughout the country, with primary focus on the south-western forest areas. The sawmills are 40 to 50 years old, well beyond the typical economic lifespan of this type of equipment. Additionally, only minimal investments have been made for repair and maintenance over the last 30 years, adding additional stress and strain to an already tired infrastructure (EFAP 1994).

The natural forest sites were selected to incorporate the different range of equipment, techniques, environment, and log sizes that occur in the natural forest harvesting operations. Harvested logs are commonly large diameter and distributed sparsely through the site. Typically, logging in the natural forests has a significant impact on the site with roads and skid trails required to be constructed in order to access the timber. The site is located at an elevation of approximately 1000 m with topography that is gently sloping. The average annual temperature is between 20 and 25° C, with a mean annual rainfall of approximately 2,000mm. While more rain falls in September than other months, there is no true rainy season in this area as rain falls year round(Abebe and Holm 2003).

2.2 Plantation Forests

Plantation forestry projects were established in the late 1960's in the south central part of the country through the work of a local development organization, the Chilalo Agricultural Development Unit (CADU) with assistance from the Swedish Development Cooperation (SIDA). Land that was previously under the direction of the State Forest Development Agency was brought under management of CADU for the establishment of the first large scale logging pand plantation projects. The existing natural forest lands were clearfelled and plantations were established on these sites and in some adjacent farmlands (Bekele 2001; Chaffey 1979). Over then next several years, approximately 6,100 hectares of plantations were established with *Eucalyptus*, *Cupressus*, *Pinus*, other exotic species, and even some indigenous species.

The forest is currently managed by the Shashemene Forest Industry Enterprise (SFIE), an organization that has some governmental ties, but is primarily lead by a board of directors and investors. There is now over 98,000 hectares of which about 6,100 hectares are in plantation forest cover and an estimated 8,000 hectares are in natural or disturbed natural forest cover. The remaining lands are in bush, bamboo, woodlands, open, or agricultural lands (Silvi Nova AB 1996). The objectives of the enterprise are to manage the enterprise's forest resources for sustainable use, generation of revenue, reinvestment of these revenues to further develop the forest resources (Bekele 2001). Additionally, the enterprise recognizes its role in rural development and the overall development of the forest products industry in the country. Even though all land and the natural resources on the land is officially owned by the state, the SFIE is in a unique situation as they have secured the rights to retain and reinvest the revenues that they generate from the harvesting and sale of forest products (Bekele 2001).

The SFIE was included in this study as they are the largest and most organized plantation forestry operation in the country. They have resources and production schedules that are relatively dependable and a desire to improve their operations. The site that was selected for this project is located in the southern part of the Oromiya State near the village of Sole (**Figure 1**). The village has a two semi permanent portable sawmills and is located less than 10 km east of the central Rift Valley town of Shashemene. A compartment was selected that was to be harvested during the field data collection time period and that was typical of harvesting areas in the district. The selected compartment was located in the Ansawae Plantation, approximately 1 km from the sawmill. The site is located at an elevation of approximately 2200 m with topography that is gently sloping. The average annual temperature is approximately 16° C, with a mean annual rainfall of approximately 1,075mm. The primary rainy season is in July and August and a smaller rainy seasons during March (Abate 2004).

Smaller scale plantations have also been established on the campus of Wondo Genet College of Forestry (WGCF), a part of the newly formed Debub University. Although the overall university is relatively new, WGCF has been involved with forestry education for many years. In 1978 the Wondo Genet Forestry Resource Institute was formed in order to provide diploma level courses in general forestry. Over the years additional efforts within the country and with assistance from the Swedish University of Agricultural Sciences (SLU) the institute was upgraded to a college and was able to offer both Bachelor and Master of Science degree programs. The only other forestry program in the country at Alemaya University of Agriculture was moved to WGCF in 1996, creating a single strong professional forestry educational faculty.

WGCF is located at the base of a large escarpment on the edge of the Rift Valley in south central Ethiopia. The campus is located approximately 10 km from the larger town of Shashemene. The campus has over 600 hectares of forest lands that it manages for teaching, research, and revenue production. Approximately 110 hectares of plantation forests of exotic and indigenous species have been established on the campus. There are an additional 490 hectares of natural forest lands that are effectively reserved from timber harvesting as they are some of the last remaining remnants of the forest that once covered this area. There is tremendous pressure on this forest from the local population, resulting in illegal pit sawing, grazing, and other damaging practices.

The campus forest plantations were included in this study because they utilize harvesting techniques that are more advanced than others in the industry. The college has many local and expatriate researchers involved in forest management, high quality maps and imagery, and access to appropriate tools and equipment that other enterprises and organizations might not have. These additional resources provide a research opportunity to investigate alternative timber harvesting processes that may not yet be implemented in other areas of the country and identify barriers that impede the knowledge transfer to the clients of the College.

The Wondo Genet (**Figure 1**) site that was selected for this project is located on the campus in the southern part of the Oromiya State near the village of Washa. Compartments were selected that were being harvested during the field data collection time period and that were representative of typical harvesting units on the campus. The plantation is located at an elevation of approximately 1900 m with topography that is gently sloping. The average annual temperature is approximately 19.5° C, with a mean annual rainfall of approximately 1,200 mm (Gindaba et al. 2004). The primary rainy season is in July and August with a smaller rainy season during March.

3. METHODS:

Each of the forest harvesting operations was observed and formal and informal interviews were conducted with different individuals and groups. Collaborative participation in the planning and harvesting process provided additional insight and details of the harvesting practices. Through this data collection process, many of the opportunities and constraints pertaining to improved forest harvesting sustainability were revealed. Data was organized and processed using a defined strategy to ensure the usability and integrity of the data. Collection and analysis of data was conducted simultaneously in order to develop interpretations that would closely represent the field experiences and interviews (Marshall and Rossman 1999). Detailed notes were recorded during all interviews, field observations, and participation activities.

An in-depth review and additional annotation was completed after data was collected to ensure that all pertinent information was properly recorded and clear. As data was accumulated, it was processed to identify prominent themes, recurring ideas, and other patterns. These concepts were then categorized in order to search for the "the salient, grounded categories of meanings held by participants in the setting" rather than the exhaustive and mutually exclusive categories of the statistician (Marshall and Rossman 1999). Data was manually coded using a generative scheme that focused on the nature and the delivery of the content in order to develop the concept categories. This process was used in order to minimize the influence of prior assumptions of possible results (Kerlin 2005). Testing the emergent patterns and concepts was completed through a process that searched contrary situations and constant comparisons with the emerging ideas in order to build a stronger overall framework theory. As the theory develops, triangulated analogous data from multiple sources, locations, and times help strengthen confidence in the overall process.

4. RESULTS

Data coding and analysis of the harvesting process revealed many prominent topics and themes. The main categories identified were: strategic planning, information resources, timber harvesting (planning, access, in forest operations, and finally landing and hauling operations).

These main topic areas were constructed into a decision framework process that could identify specific issues and develop solutions to improve forest operations sustainability.

This decision framework combines core sustainability concepts of environmental, economic, and social responsibility with forest harvesting operations. This process facilitates the collection of necessary site specific information and provides the structure to develop appropriate, sustainable improvements to current forest harvesting operations. The framework is broken down into five phases: strategic guidance and purpose, information and data (available information resources), harvesting process, solutions and outcomes, and ranking and prioritization. (**Figure 2**). This approach uses the principle categories and themes identified in the data collection phase with decision support concepts to develop solutions that meet the particular needs of an organization, site, or individual.

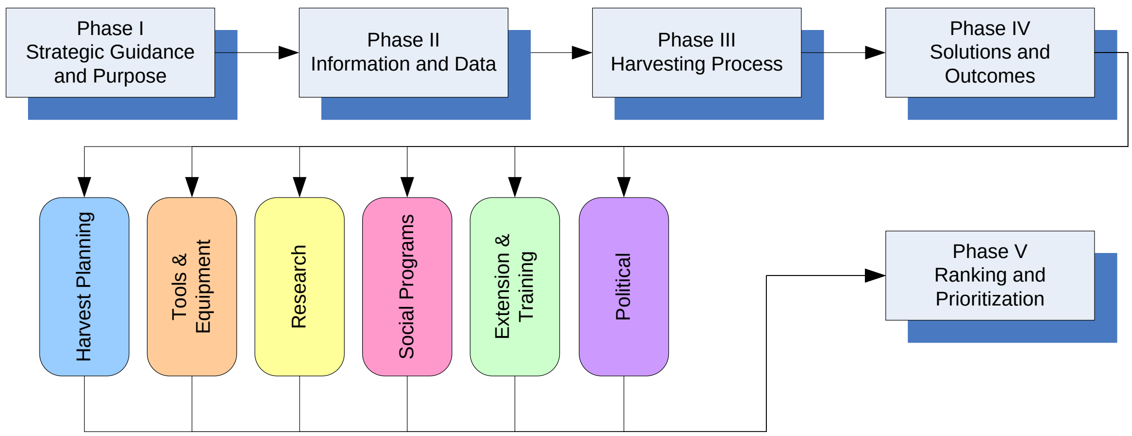

Figure 2. Five phase sustainable harvesting improvement identification decision framework

In the first three phases of the framework, similar questions covering different operational levels of timber harvesting programs are answered to develop an understanding of the overall situation. This process starts with the identification of basic sustainability issues, current conditions and issues, and potential improvements. Following collection of this data, expected outcomes are identified and a priority is assigned to the particular issue. This process provides the researcher the ability to develop an understanding of the local situation through experiences and interviews with many different levels in the organization, before generating solutions and outcomes to be implemented. Phase III (Forest Harvesting) requires the most effort in order to cover the full breadth of different operations and sample of involved people. This phase generates large quantities of data as many levels of the organization and local communities are involved. Upper management and day laborers both have potential feedback about the harvesting process at this level, where day laborers may have limited exposure and therefore input to some of the other phases such as strategic goals, long term planning, and operational data requirements.

The data collected during the first three phases produces a collection of different issues and opportunities to improve forest harvesting operations. Potential solutions both large and small along with ideas of priorities and scope of impacts from the first three phases will be collected in Phase IV (Solutions and Outcomes). In this phase different identified potential solutions are grouped into broad solution categories of harvest planning, tools and equipment, research, social programs, extension and training, and political. This process combines the diverse range of solutions into action areas that can be addressed by different individuals, approaches, or financing. Solutions in the political category may be more difficult to implement unless an organization has sufficient political influence, whereas the tools and equipment solutions may be relatively simple with the purchase of an inexpensive hand tool or locally produced sulky (Seymour 1996). Once solutions have been grouped, each of the categories should be prioritized and ranked for implementation (Phase V). Many tools are available to facilitate this process ranging from simple ranking, composite scoring, and more complex systems such as analytical hierarchy process procedures and multi-criteria decision making tools.

5. DISCUSSION

In field timber harvesting experiences and data collection provided the required range of information to develop a decision framework that responds to the environmental, economic, and social conditions in Ethiopia. These local responses and experiences provide the germane areas of concern without unnecessary emphasis on topics of little interest and relevance. On the other hand, topics that were frequently repeated by multiple respondents are elaborated and elevated in the process to develop meaningful and implementable solutions. Without on the ground interactions, the prescription of existing approaches to timber harvesting from the temperate or the more developed regions might dictate improvements that may not be appropriate, possible, or provide the desired benefits. In many cases the best solutions and improvements come from within, from the people closest to the activity. The use of social science research methods to have participants lead discussions and the development of ideas provides solutions that are grounded in the actual environment and chances for successfully improving operations are good. Simply imposing solutions best suited for European or American forest operations fails to recognize the unique local sustainability conditions of focus in this study.

In the use of this framework, a small group of researchers would be used to collect local data from respondents and other activities utilizing common development tools and techniques that are designed to provide ownership to the local groups. The research group will lead the collection of data from experiences, observations, and through guided informal interview discussions that attempt to encourage a broad examination of the range of possible issues and opportunities. If left to simple discussion without guidance through the decision framework, identified solutions and issues were often rudimentary and failed to probe issue areas and potential solutions covering multiple concepts or layers of an operation.

The use of multiple research sites attempted to address the wide range of different harvesting conditions in Ethiopia. Issues and solutions in the natural forest area have some similarities to those in the plantation forests, however both areas have unique and important components that need recognition in any decision tool. Even the two different plantation forest operations of the SFIE and the WGCF each have distinct characteristics that provide additional enrichment. By incorporating experiences and data from all research sites, the overall decision framework recognizes the scope of potential differences. This also challenges participants to be aware of other harvesting operations conditions and types to develop solutions and avoid pitfalls in their own operations. While sites in Ethiopia were used to develop this framework, many parts of the developing world face similar questions and situations that fall into the same categories for decision making. This decision framework would be appropriate in other areas outside of Ethiopia with appropriate adjustments for the local conditions.

6. CONCLUSION

Forest utilization is an important component in the daily lives of most Ethiopians for fuel, fodder, coffee cultivation, and other many other uses. Improvements in commercial forest harvesting to move towards more sustainable operations can help decrease the impacts of this one type of forest utilization. A decision framework has been developed using experiences and discussions with those involved with many different levels of operations. This development process has incorporated social science data collection processes and harvesting operations in different organizational and physical conditions in order to capture diverse issues and appropriate solutions. Through use of this decision framework, solutions to improve the economic, environmental, and social conditions of operations can be identified and implementation planning can begin.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Skyline Systems in Appalachia – two years hence*

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Abstract
A skyline logging company was established in the central Applachian coal mining region four years ago. This report updates a previous report given to COFE during the Hot Springs, Arkansas meeting two years ago.

1. INTRODUCTION

I have been directly involved in skyline logging operations since 1975, as a foreman/engineer, business owner, practitioner, trainer, and consultant.

In years past our operations have been based within the Western Montana and Northern Idaho region. We have also had the opportunity to operate on the West Coast, Southeast British Columbia and the forest regions of Chile.

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 71-76.*

2. REVIEW

We established a skyline logging business in the coal country of the central Appalachians of Virginia about four years ago and planned to continue with it for five years. This report is an update to one given to this group two years ago at the COFE Hot Springs meeting.

Successes are a pleasure to relate to colleagues. However, our venture into the central Appalachians, although not all negative, was in my estimation a business failure. Reflecting and learning from such a setback is difficult, but nonetheless part of the process for molding future endeavors.

I want to share with you some of these reflections. Perhaps you can provide further insights.

3. THE DECLINE

Above all, it was a management failure. 'The buck stops here' quote applies. One can think of many reasons for this failure. I was the decision maker and the only one responsible for the outcome.

Realizing the risk of the venture there was a substantial and costly effort with regard to due diligence. Visiting, interviewing, reconnaissance, collecting cost information, analyzing, planning, trying to cross check information, and on. A diligent effort was made before crossing the welcome mat presented by millers in the area. With our business plan in hand, trust in the people we would work for, and a leap of faith I decided to forge ahead with the plan.

Two years later, in quotes from my report at the COFE Hot Springs meeting, there was, in a final summary, still a tone of cautious optimism.

"Everyone realized the labor market would be a real challenge, but not insurmountable."

"…, I am confident that we can accomplish our mission as we continue to improve our strategic plans, training, having faith in our employees, and keeping our machinery in a well maintained condition."

The wild card proved to be labor. Not being able to find the right labor formula within a reasonable timeframe proved to be the fatal flaw in the business plan.

Factors such as climate, forest resource, terrain, and infrastructure were workable. Within this 'natural environment' the combination of Men, Machinery, and Methods had to come together as a safe, productive, and profitable entity. Operational planning methodology was good. The machinery was properly sized and ran well. The workforce was a real challenge and finally proved insurmountable.

Figure 1 illustrates productivity per week during the last harvesting project.

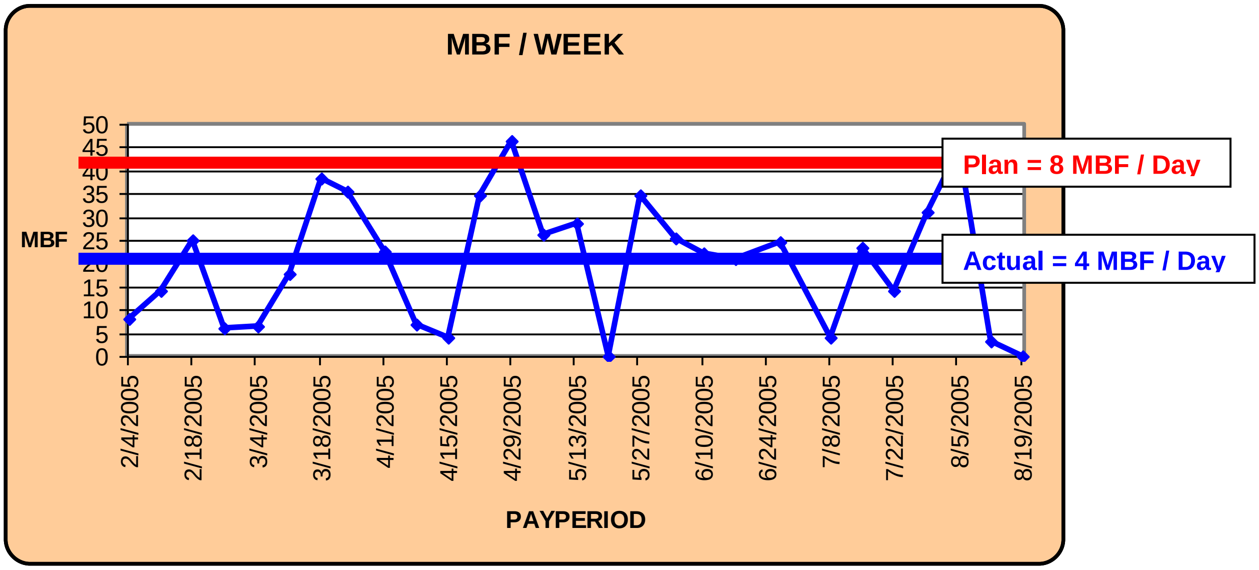

Figure 1 - Weekly production on last major project

Actual productivity was quite variable. It resembles a profile of the Rocky Mountain Range rather than the Cumberland Plateau. The average rate of production (solid blue horizontal line) was half of the minimum planned 8 MBF/Day, Doyle Scale (solid red horizontal line). This is strikingly less than our typical daily production achieved in prior operations in small softwoods of 12 – 20 MBF/Day, Scribner Dec. C Scale.

These large fluctuations in weekly production were primarily crew driven, which includes direct employees and contract truckers. Absenteeism due to 'sickness', lack of motivation, rainy weather, various personal appointments, family matters, mini-vacations, and real and feigned injury, et al. affected productivity the most. When a crew of 6 is needed and there are 3.5 for the week, production does not even approach the doable 8 MBF per day. Mixed in with normal downtime events and muddy road access, weekly productivity translated into a very poor average cash flow. The bookkeeper (my wife) struggled and juggled to try and meet debt, payroll, and other payments. It was a daunting and discouraging task. It was mentally and physically trying. It was a time to cut the losses.

4. THE END

The Coal Industry has been and continues to be the region's dominating industry.

Over the past year and a half large increases in the ton price of coal (from approximately $25 / Ton to $60-100 / Ton) made it financially attractive to expand existing and reopen previously marginal mines.

The pressure placed upon an already marginal local labor supply by coal industry expansion was our final 'nail in the coffin'. Although we were told by mill people, employees and log haulers that we paid more than other contractors the wages and benefits offered by the coal industry were considerably more than we could offer. The last 9 months of yarder logging was basically a 3.5 man operation, including loader operator. The last month of operation was a two man skyline yarder operation.

Upon completion of our contractual obligations we derigged and moved the equipment to a storage area in September, 2005. Since then we have been gradually selling off equipment to pay down debt (Figure 2).

Figure 2 – Equipment sold to companies out of local area

5. LOOKING BACK

5.1 Due diligence

Although a concerted effort was made to assess the opportunity, even more time could have been invested in research. For example, discussions with insurers familiar with workmen's compensation, general liability, and equipment loss data could have provided further insights. Going to clinics and hospitals to glean some characteristics of the labor force could have also provided some information concerning workforce mentality.

5.2 Labor Sources

Labor Search

- Word of mouth – from employees, truckers – typically a relative
- VEC – counselor / on list – trouble finding motivated people
- Job Corps –USFS – not tough enough, work was too hard
- DOL approval for 7 foreign workers – lengthily and cumbersome process
- Interviewing foreign labor – were established in tobacco cutting and landscape rock
- Work Release Program at County Jail – stepping stone to other endeavors
- Advertising out west – most afraid of snakes, don't want to move
- Community College forestry program – no takers, work did not allow sleeping in pickups
- Other contractors ideas – neighborly, but not sincere
- Mill recommendations – too far from the real action
- Cable TV Ad – reaches the stay at home crowd
- Parts houses/Saw shops – some success
- Chamber of Commerce – say there is a ready supply of labor – but mainly to staff call centers

Figure 2 – Labor source options

Figure 2 illustrates most of the avenues we employed in the search for a crew.

We began to hire crew through the Virginia Employment Commission. They were helpful and responsive. However, we were not successful in accumulating enough motivated employees.

Virginia employment officials told me that historically the area had a hard working labor force. But, after more than two generations of "Great Society" programs, which enabled a large number of people to live without working, many young workers now lack any kind of work ethic. This, I discovered, is also a constant challenge for other employers in the region. A police officer in a neighboring county explained to me that only 15% of the people in the county were wage earners.

Consequently we went through the hiring-firing-quitting process with many young men in the 20 to 40 year old bracket.

In comparison to previous operations we had the same core employees, with some turnover around the fringes of the core. Our longest employee worked for us for 18 years; timber fallers between 10 and 15 years; a hooktender about 15 years; loader operator 15 years; contract truckers variable, but many 10 – 15 years in service. These were young men, proud to be loggers. They principally worked on a production basis.

Twenty-five to thirty years ago I was exposed to alcohol abuse in the workplace, firsthand. Then, drug usage started creeping into the labor force. We had to contend with it, but seemed to manage. A couple of our principal employees experienced what was termed a drug/alcohol intervention. Without warning they were confronted with their problem. With the consent of their family members we had arranged to send them to a rehabilitation center for some months. They returned, renewed and motivated. Their self discipline lasted only a few years. Alcohol and drug usage would gradually start again, typically triggered by a non-supportive spouse or some other family stress. However, we were still able to function and produce with these same men with very little absenteeism.

In comparison to what I have experienced in the central Appalachian region is a more pervasive usage of drugs of various types. Is it unique to this region? In my opinion, no, it is a nationwide, even global trend. Was I experiencing a microcosm of society spiraling ever downward with the abuse of more dangerous and more addictive chemicals? I suspect so. At that time and in that setting, I do know that I experienced a much greater percentage of drug abuse in this region than in others. The fruit of this addiction is rampant absenteeism, short attention spans, less healthful physiques, lack of motivation to learn, etc.

Drug and alcohol abuse continue to take its toll upon able bodied young men and those with young families. It is a continuing scourge upon our society crying out for solutions. All fronts need to be attacked: individual responsibility and self discipline; corporate stewardship of employees; and, a society continually molding the legal framework to guide the proper use and reduce the abuse of these chemicals to non-destructive levels.

5.3 Observations

As we closed the doors the following retrospective observations could be made:

- Competing with the coal industry was not possible. Higher wages, benefits, and associated insurance costs based on gross payroll could not be absorbed with the contract logging rate.
- The cost price squeeze is alive and well. Family businesses that employ only family members can avoid the expense of workmen's compensation insurance; paying in cash is also a known practice. This allows the timber investment companies to keep logging costs as minimal as possible under the shield of the independent contractor rules.
- A stump to dump operation would be necessary as local contract haulers were not a consistently dependable lot.
- An attempt was made to hire qualified foreign labor. Through a lengthy application process, the US Department of Labor (DoL) authorized our company seven foreign workers. This strategy was abandoned because we were still faced with a cumbersome process, additional costs, and considerable time yet to be incurred. However, with hindsight knowledge of the process and timeline considerations it could have been a viable option. We had exhausted most avenues we knew of to hire fellow citizens before applying to the DoL. Gross negligence in the enforcement of immigration laws created an uneven playing field for those going through legal channels for foreign labor.

6. SUMMARY

The experience had similarities to acclimating in a foreign culture. It takes time. As we all know logging is not for the faint hearted. It is not easy to get up early and come home late, travel long distances to the jobsite, work in all weather and terrain conditions, and pull repair and maintenance where the machinery sets.

There are other occupations that reward potential loggers greater than logging. So, the push for mechanization will continue. If the past is any indicator, neither the timber investment companies nor millers are likely to support higher wages and basic benefits to attract and keep a professional workforce.

For typical contractors, where lack of a reliable labor source is critical, motivated foreign labor would appear to be a reasonable option.

My advice to others who may be given the same opportunity is to conduct an extensive due diligence process; no question asked is an irrelevant question. Don't block your intuitive impulses. Be aware with whom you are negotiating. Where are they in the chain of command? Additionally, a fair request would be a formal agreement that shares your significant risk with those wanting your unique services.

2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

An Overview of Helicopter Logging in British Columbia*

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Abstract
Helicopter logging is currently used to harvest about 8 000 000 m^3 of timber in British Columbia each year. B.C. possesses some of the most advanced helicopter logging techniques and skill sets in the world. Helicopter logging is often used to address environmental and/or operability concerns on the province's steep, sensitive and/or remote commercial forest land. The high cost of the harvesting system has created an atmosphere among those involved in helicopter logging centered on improving harvesting productivity and reducing operating costs within the confines of environmental and safety directives. Innovative new harvest techniques, skill sets and strong attention to planning and field engineering have become paramount to B.C.'s helicopter logging community. The following paper details the current state of helicopter logging in B.C. from an operational prospective and discusses several planning and layout factors which have significant impacts on operational efficiency.

1. INTRODUCTION

Helicopter logging has realized significant operational advances and forest industry acceptance in British Columbia over the past decade. This system is now used to harvest approximately 10% of the province's Annual Allowable Cut (AAC) or about 8 000 000 m^3 per annum. Today many forest companies in B.C. rely on helicopter logging on areas that are deemed environmentally sensitive, inaccessible or outside of current regulatory operability limits. Additionally, helicopter logging is often used to capture short-term market opportunities or to reduce de-grade of high value logs. Due to the highly competitive nature of the business, the helicopter logging community in B.C. is continually innovating and consequently the techniques and skill sets used are among the most advanced in the world.

2. HELICOPTER LOGGING IN BRITISH COLUMBIA

2.1 Advantages and disadvantages of helicopter logging in British Columbia

As with any harvest system, helicopter logging has a clear set of advantages and disadvantages which determine if it is an appropriate system for a specific stand and site. Table 2 outlines the important operational advantages and disadvantages.

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 77-83.*

Table 2. Advantages and disadvantages of helicopter logging in British Columbia

Advantages	Disadvantages
Extends operability limits	High cost
Expands operable forest land base	Increases the difficulty and cost for silviculture obligations
Reduces or eliminates road building	High susceptibility to poor weather
Reduces cutblock harvesting disturbance	Requires relatively large landing areas
Advantageous for capture of short term market opportunities	Requires a greater number of trucks and sort yard requirements
Allows flexible cutblock design	Requires strong operational coordination
Well suited to partial cutting	Not suited to low volume or small projects
May reduce visual impact from harvesting	Requires a high level of falling expertise
May reduce breakage	

2.2 Helicopters and rigging systems in use in British Columbia

B.C.'s highly variable operating conditions, range of timber sizes, and market competition have resulted in the utilization of a diverse group of light, medium and heavy-lift[1] helicopters and rigging systems. Currently, thirteen helicopter models carry out most, if not all of the helicopter logging in the province (Table 1), with light-lift helicopters operating mainly in B.C.'s interior and medium and heavy-lift helicopters operating mainly on the coast of B.C. where timber and per-log payload is comparatively larger.

Table 1. Specifications for helicopters commonly used for logging in B.C.

Manufacturer	Model	Rated payload capacity (lb.)	Engines (no.)	Engine power [b] (kW)
Bell	204B	4,000	1	820
Bell	205A	5,000	1	1 044
Bell	212	5,000	2	671 (each)
Bell	214B	8,000	1	2 185
Boeing	V-107 II	10,500	2	932 (each)
Boeing	CH-234LR	28,000	2	3 039 (each)
Sikorsky [c]	S-64E	20,000	2	3 356 (each)
Sikorsky [c]	S-64F	25,000	2	3 579 (each)
Eurocopter	A-Star B2	2,560	1	732
Eurocopter	SA-315B Lama	2,500	1	640
Kaman	K-1200	6,000	1	1 342
Kamov	KA-32A	11,000	2	1 645 (each)
Sikorsky	S-58T	5,000	2	700 (each)
Sikorsky	S-61N	8,000	2	1 044 (each)
Sikorsky	S-61N Shortski	9,000	2	1 044 (each)

[a] Helicopter capabilities will vary with flight conditions and installed options.
[b] Engine power at takeoff.

[1] In general logging helicopters are classified on the basis of their maximum rated payload as either light-lift (less than 10 000 lb.), medium-lift (10 000-15 000 lb.) or heavy-lift (more than 15 000 lb.).

[c] Now manufactured by Erickson Air-Crane Inc.

Three main rigging systems are used: hook, grapple and standing stem. Several hybrid systems exist which combine one or more of the primary systems with either manual or mechanical falling. Some examples of these will be discussed later in the paper.

Helicopter hook or choker yarding is the most common rigging system and makes use of chokers attached to a hook which hangs on a long-line from the belly of the helicopter (Figure 1). However, the use of helicopter grappling, a hydraulic or electrically actuated grapple (Figure 2) attached to a long-line, has increased greatly over the past several years for a number of reasons including smaller crew size and consequently improved safety[2].

Figure 1. Helicopter hook

Figure 2. Light-lift helicopter grapple

Standing stem helicopter logging was pioneered in B.C. Although it makes up only a small proportion of the volume helicopter logged, it brings some of the highest value timber to roadside each year. This technique harvests full length trees from the standing position. The trees are selected according to certain criteria including species and grade (usually those of high value). The selected trees are climbed, and delimbed and topped by chainsaw, the trees are then "cut up"[3] (Figure 3) and yarded using a horizontally oriented grapple (Figure 4). During this tree preparation phase, each tree's location is recorded and its volume and approximate weight are calculated. Prototype development and testing are underway of a mechanical apparatus which hangs from the belly of the helicopter and mechanically delimbs, tops, cuts and yards the stem.

[2] Helicopter grappling generally yields a lower flight hour production rate because meeting target turn payloads is typically more difficult and building multi-log turns can take a considerable amount of time if logs are spread out.

[3] Two cuts are put into the tree, one on each side of the stem. A small piece of holding wood is left off-centered in the direction of the natural lean of the tree.

Figure 3. A cut-up standing stem tree

Figure 4. S-64E standing stem operation.

As mentioned, several hybrid systems also exist including grapple/choker[4], fly-in-feller buncher, fall-around-yard-around and jack-over systems.

The fly-in feller-buncher system was developed in B.C. as a result of the shift towards harvesting more small-stem second and third growth timber. This system enables efficient use of heavy-lift machines in smaller timber by utilizing a custom-built feller buncher which can be broken into eight pieces for aerial transport into a cutblock. Bunching enables the heavy-lift helicopter to achieve target payloads without spending additional helicopter time to build turns (Figures 5 and 6).

Figure 5. Fly-in feller -buncher

Figure 6. Cutblock after bunching.

The fall-around-yard-around and jack-over systems are by-products of standing stem harvesting. Fall-around-yard-around combines standing stem harvesting with the use of a feller-buncher to enable economic maximization of high value trees within a stand as well as increased yarding efficiency by bunching felled trees.

The jack-over system is used for large, high value trees which are too heavy to lift off the stump during standing stem harvesting. Instead, the trees are manually limbed, topped, banded

[4] A combination of heli-hook and heli-grappling which requires fewer crew members working in the cutblock than a conventional hook operation. This system eliminates some of the production penalties associated with conventional grappling. Logs in a turn are choked to a main log, often referred to as a "pick" log and the "pick" log is grabbed with the grapple for yarding.

and jacked over to reduce breakage and shatter. Once on the ground the trees are bucked for quality and weight and yarded out with a conventional grapple equipped helicopter.

2.3 Helicopter logging production rates and costs in British Columbia

Helicopter logging in B.C. is a costly yet highly productive yarding system with per shift productivity rates as high as 1 800 m^3 for some heavy-lift helicopters, including the Erickson S-64 and Boeing 234 Chinook[5]. Medium-lift helicopters, e.g., the Kamov KA-32 and Boeing Vertol 107, generally produce about 50% of a heavy-lift helicopter's production given similar shift and operating parameters. A light-lift helicopter will typically generate 50-70% the production of a comparable medium-lift operation.

Variations in rigging systems also affect yarding production. A helicopter hook system typically produces 20-30% more than a comparable grapple yarding operation and 5-15% less than a bunched or standing stem operation given similar shift and operating parameters and that timber size is well suited to helicopter payload specifications (Table 3).

Table 3. Average production ranges in B.C. for various helicopter lift categories by system

	Hook (m^3/flight hour)	Grapple (m^3/flight hour)	Bunching for grapple (m^3/flight hour)	Standing stem (m^3/flight hour)
Heavy-lift	145-175	110-140	155-210	150-200
Medium-lift	70-85	55-70	80-100	75-100
Light-lift	40-50	30-40	45-60	45-60

Helicopter logging operations have several cost centers. In general, ownership and operating costs for the logging helicopter alone comprise the largest portion of total cost and typically account for 50% or more of the total stump-to-truck harvesting cost. Heavy-lift helicopter ownership and operating costs on a flight-hour basis are very high, ranging from $7 000 to $9 000 (CAN), with medium-lift and light-lift ownership and operating costs between $2 500 to $4 000 (CAN) and $1 000 to $2 500 (CAN) respectively.

2.4 Planning and field engineering factors influencing production and operational costs of helicopter logging in British Columbia

The high cost of helicopter logging in B.C. has created an atmosphere among industry, agencies and contractors centered on improving harvesting productivity and reducing operating costs within the confines of environmental and safety directives. Forest planners and field engineers in B.C. are charged with carrying out effective field layout and harvest scheduling to enhance production and operational costs of helicopter harvest operations. Planning and layout factors such as flight distance and flight path slope, cutblock and landing design, harvesting prescription, time of harvest and in-woods manufacturing regimes have significant impacts on operational efficiency. The following provides details on some key planning and field engineering factors which can have a significant impact on helicopter logging productivity and operational costs.

[5] Based on 8-9 flight hours per shift.

2.5 Flight distance and flight path slope

As a general rule, most helicopter logging contractors in B.C. do not like to exceed flight distances of 800 m and/or descent flight path slopes beyond approximately 35% during loaded flight. Minimizing flight distance without compromising optimal flight path slope or landing requirements can have one of the greatest impacts on helicopter logging production (Dunham 2002). However, minimizing flight distance at the expense of increasing flight path slope beyond the outer limits of 35-40%, typically results in reduced descent speeds or deliberate lengthening of flight path in order to maintain safe helicopter flight under load. Additionally, helicopter logging productivity can be reduced if flight path slope is flat (or close to flat) because the helicopter is required to dead-lift turn weight above the stand's canopy before beginning forward flight and therefore is unable to use the advantage of gravity on descent. Dead-lifting generally results in a reduction in turn payload because more torque is required by the helicopter during breakout.

2.6 Cutblock design

Often cutblock design in B.C., especially in steep terrain, is dictated by environmental limitations. Helicopter logging cutblock design, where possible, should be geared towards the type or lift category of planned helicopter, the rigging system, and the in-woods crew complement, if applicable. The use of multiple cutblocks or landings in an operation can also affect cutblock size requirements. For a helicopter hook operation, it is important to design a cutblock large enough to accommodate an adequate number of rigging crews in order to keep the helicopter supplied with wood. Cutblock layout containing isolated corners often makes the placement of rigging crews difficult and prevents the helicopter from utilizing a good loaded glide path, without necessitating dead-lifting to get above the tree-line. Predominantly square or horizontally-oriented rectangular cutblocks provide for the easiest and safest crew placement. When designing small patch-cuts, tear-drop shaped patches or vertically oriented rectangular patches allow easier turn breakouts and enable the helicopter to begin forward flight while gaining lift.

2.7 Landing design

Ideally, log landings should be located to facilitate the most direct route from the cutblock(s) while taking into account factors such as flight path slope, predominate wind patterns and potential obstructions. Inadequate landing size often results in a plugged landing which either forces the helicopter to shutdown until the landing can be cleared or increases turn release time and potential landing hazards. When determining an adequate size landing, factors such as helicopter selection, landing equipment, crew size, average log length, waste wood storage requirements and the number of cutblocks and associated landings concurrently scheduled for harvest should be considered.

Furthermore, during the layout of service landings, consideration needs to be given to the size of the helicopter, the amount of maintenance support equipment required, adequate protection from weather and wind, and again flight distance and flight path slopes.

2.8 Harvesting prescription

Many B.C. based forest companies have adopted a practice of non-clearcut retention logging in order to meet environmental and public pressures. Planners, field engineers and helicopter logging contractors working in B.C. acknowledge production penalties associated with retention logging but find these penalties difficult to quantify. FERIC's results from helicopter logging production studies over the past 15 years indicate per flight hour production penalties can exceed 5% and 15% for patch cut and single tree selection harvests, respectively, when compared to clearcuts (Krag and Evans 2003).

2.9 Time of harvest

Weather and climatic conditions are the most detrimental factors affecting helicopter logging in British Columbia because helicopter use is greatly affected by fog, wind, air temperature and altitude (Dunham 2004a). B.C. has one of the most varied environments in the world, so planners need to use local weather information to determine the most optimal time of year to schedule helicopter logging operations in order to decrease weather related downtime. Typically, late spring, summer and fall are the best times to carry out helicopter logging activities in B.C.

2.10 Helicopter selection

Some forest companies operating on B.C.'s coast have entered into joint management/operating partnerships with helicopter logging contractors which typically enhance field engineering because engineers are familiar with the helicopter being utilized. Like any machine, all helicopters do not have the same abilities and requirements, so identifying the helicopter or at least the lift category of helicopter best suited to the cutblock's average tree size, silviculture prescription and flight path regimes, and then designing the cutblock to take advantage of the helicopter's attributes, can have considerable impact on yarding production.

2.11 In-woods manufacturing regime

Helicopter logging contractors typically strive for waste wood levels under 7% but, this target is often exceeded. Careful in-woods manufacturing generally reduces overall helicopter logging costs because non-revenue wood is left on-site rather than yarded (Dunham 2004b). Even though falling productivity decreases and costs increase as the level of in-woods manufacturing increases, the reverse is true for helicopter yarding productivity and costs which represents the greatest portion of total harvesting cost.

3. CONCLUSION

Helicopter logging is a state of the art forest practice unrestricted by many cable or ground-based harvest system limitations. Highly variable operating conditions, a large range of timber sizes and strong market competition have made the helicopter logging community in British Columbia extremely innovative with skill sets and techniques among the most advanced in the world. Although helicopter logging is expensive in comparison to other harvest systems, it is highly productive. Often it is the only system which can successfully address environmental and operability concerns in areas of steep, sensitive and/or remote commercial forest land in the province. Approximately 10% of the province's AAC is harvested with helicopters and that number is expected to increase in the future.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

An Analysis of the Yarding Operation System with a Mobile Tower-yarder in Korea*

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Abstract
This study was conducted to investigate the efficiency of yarding operation, the yarding operation system, the optimum lateral yarding distance and setting-up spacing in order to establish the optimum yarding operation system with a mobile tower-yarder in Korea.
In line thinning yarding operation by a mobile tower-yarder (RME-300T), the ratio of choker setting and lateral yarding time among productive time element was the highest. An average yarding productivity of a mobile tower-yarder in line thinning operation was 5.25m^3 per a man-day. As the results of the simulation of yarding operation by RME-300T mobile tower-yarder, the total yarding time for one corridor with 7 planting rows of one block and 1 ha took about 1.7 day and 5 days, respectively. And in the yarding operation of the line thinning and clear cutting with a mobile tower-yarder, optimum setting-up spacing was about 20 m and 11 m, respectively.

1. INTRODUCTION

In the 19th century, there were lot of old growth forests in the northern and eastern parts of Korea, although most hills and mountains are devastated and the destruction of the natural forests surrounding of Seoul especially excessive. After severe over-cutting and illegal cutting for construction materials and fuel throughout long periods of the Japanese occupation (1910~1945) and of the Korean War (1950~1953), the average stock volume of forests in 1960 was only 10.6m^3/ha. After successful fulfillment of very strict and deliberate reforestation policies of forest authority (Korea Forest Service) during several decades, the most if the devastated forest lands have been converted to well stocked artificial forests.

Based on the 2004 forest statistics, the forest area in Korea is 6.4 million ha, covering about 64.3% of total land area. About 1.47 million ha, 23% of the entire forest area, are national forests, 0.5 million ha or 7.6% are public forests, and the remaining 69.4% are private forests. The forest area per forest owner, however, is as low as 2.2 ha which is very unfavorable ownership structure for rational management. Total growing stock is 489 million m^3 with stock volume per ha estimating to 76.4 m^3. Almost 59% of forest stands are under the age of 30 years. Thus, Korea has largely depended on imported timber, supplying about 94% of domestic timber consumption, and self-sufficiency rate is merely 6%, and the demand and supply of domestic timber is increasing. Recently various tending activities such as natural forest tending and thinning have been undertaken to produce high-quality timber resources. Specially, forestry mechanization has been emphasized in thinning and timber harvesting. As of 2003, 15,510km of forest road was constructed, however, forest road density is merely 2.42m per ha (Korea Forest Service, 2005). The forest land in Korea is consisted of mountainous and steep slope terrain. Several cable logging systems were introduced during 1980s from Japan and Europe to facilitate the thinning operations in plantation forests, which were established in mid 1970s and 1980s.

Several field studies for logging systems were carried out to determine the productivity and operating cost and also to find out feasibility of their application in Korea (Noh *et al,* 1988; Ma, *et al,* 1997)

This study was conducted to investigate the efficiency of yarding operation with tower yarder RME 300T, with running skyline rigging system. To find out the influencing factors to yarding productivity, several analyses of cycle time elements and some variables were done.

2. STUDY METHODS

2.1 Study site description

A summary of the investigated site and yarding conditions is shown in Table 1. As shown in Table 1, the study area was divided into two separated location A and B, which were located at urban area in Daegu city and Jinangun, Cheonrabukdo respectively. Two sites had different site characteristics of tree species and operation method, although they showed similar DBH classes of premature coniferous forests with different tree heights. In study site A, the forest type was plantation of Korean white pine (Pinus koraiensis) which showed 0.057 m^3 unit volume of average felled trees. The thinning ratio was 50% as the stand was overstocked according to the stand table. Thinning operation method was line thinning which was every other planting line was cut and extracted to uphill direction. In study site B, the forest type was plantation of pitch pine (Pinus rigida) which showed larger average tree size of 0.154 m^3/tree than Korean white pine of 0.057 m^3/tree. The pitch pine stand was clear felled due to severe damage of pitch canker (Fusarium spp.), and the pine forest had been planned to be converted to other broad leaved tree species after felling and site preparation.

2.2. Equipment and logging operation used in study

A mobile tower-yarder used in this study was a mobile tower yarder mounted on terrain vehicle (Model: RME-300T), which had been manufactured by Oikawa Motors Co. Ltd. in Japan (Figure 1). The base vehicle of this tower yarder equipped all wheel drive system with 6 wheels, and its driving speed was 15 km/hr in maximum. The terrain vehicle was widely used as small forwarder in Japan and it can move easily on steep skidding trail with its excellent climbing ability of 35°. The tower yarder had a steel tower of 9m height installed on rotatable platform, which could be rotated 360° in any directions. The winch driving system of the tower yarder equipped two groove wheels, which were controlled by an electric clutch and interlocking functions were fulfilled by automatic synchronization of the rope speed for mainline and haul back line drum. The RME-300T had three drums of mainline, haul back line and skyline, and it could be applied for running skyline systems with two drums of mainline and haul back line. It could be also applied as fixed skyline system using mainline and haul back line drums of 350m (Ø9mm) and 650m (Ø9mm) respectively, and its maximum yarding length is 300m and traction force of each groove wheel was 1,500 kgf. The RME-300T could be is controlled by remote controller connected with 10m cable and it could be operated with two operating modes of automatic interlocking (synchronized line speed with coupled clutches) and non-interlocking manual mode (independent speed control of each drum).

Figure 2 shows the working procedure of logging operation during study from felling to transport of the logs. Felling was carried out with one-man chain saw, and full tree yarding method was applied by two men crew with the tower-yarder RME-300T. The stacked yarded trees on road side were removed occasionally by an excavator with log grapple after extracted trees formed some heaps as it. Delimbing and bucking were done concurrent with the yarding phase. The full tree system was applied also in thinning site (Site A) and clear cutting site (Site B)was applied. Bucking in 1.8 m short logs for pulpwood is enforced by one man with chainsaw at forest-road or landing.

Table 1. The investigated location and stand conditions.

Items	Site A	Site B
Investigated location	Daegu city	Jinan-gun, Cheonrabuk-do
Total area	27.6ha	6ha
Average slope	24°	30°
Forest type	Plantation	Plantation
Species	Korean white pine (*Pinus koraiensis*)	Pitch pine (*Pinus rigida*)
Stand age	26 years	35 years
The number of standing trees	2,000 trees/ha	1,200 trees/ha
Average DBH	15.8cm	16.0cm
Average tree height	9.4m	15m
Average tree volume	0.057㎥/tree	0.154㎥/tree
Average growing stock	114.0㎥/ha	184.8㎥/ha
Thinning intensity	50%	-
Operation method	Line thinning	Clear cutting
Yarding direction	Uphill	Downhill

Figure 1. Tower-yarder RME-300T.

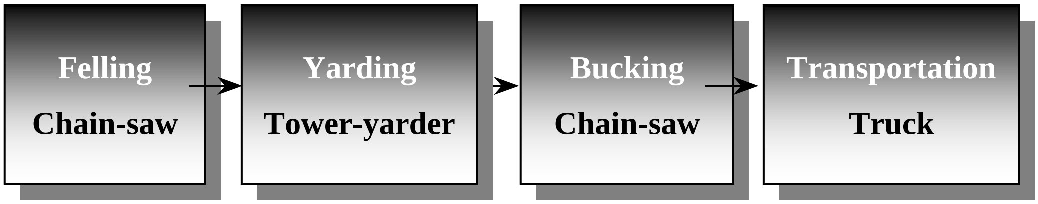

Figure 2. The working procedures of logging operation study site A and B.

2.3. Methods

During the yarding operations with by a mobile tower yarder RME-300T, the time study was executed with stop watch to quantify the individual cycle elements. Time study method was continuous timing and productivity affecting factors such as harvested cycle volume and yarding distance were also recorded with each operating time element. And whole operation system was evaluated through analysis of the recorded results and the yarding operation efficiency was calculated based on the observed total yarding times and the harvested timber volumes. And to estimate the productivity of yarding operations with tower yarder RME-300T, some relationships between selected time elements and yarding distance factors were analyzed using the observed time element data.

3. RESULTS AND DISCUSSION

3.1 An analysis of yarding time element

In the study site A of line thinning operation, observed total working time was 169.03 minutes for 35 yarding cycles. The percentage of productive time (main operation time) in total working time was 64.8% and non- productive time (accessory operation time) was 35.2%. In productive time, the component ratio of choker setting, lateral yarding and yarding time element were shown 18%, 14% and 11%, respectively (Figure 3). In figure 3, the component ratio of choker setting time element was the most time consuming element because setting the choker on two trees at a time was not easy in running skyline system and the skill of the choker man was not enough. Also for lateral yarding, took 0.45 minute to prevent the damage to residual standing tree or avoid the hang up. Also lateral skidding distances for each side of corridor were three planting rows of 7.2 m in line thinning. It is necessary to train the choker setter in order to shorten the choker setting time and enhance the system efficiency of the tower yarder operations.

And among the non-productive time elements, setting-up and dismantling the running skyline rigging and delay time components (operation standing time) showed 67%, 15% and 12% of total non-productive time, respectively (Figure 4). In figure 4, the high component ratio of setting-up and dismantling time is general results in the yarding operation with a mobile tower-yarder. This Therefore, it is necessary to training in order to reduce the setting-up and dismantling time.

Table 2 shows the results percentages of time elements per turn during line thinning operation with RME-300T mobile tower-yarder at study site A. The component ratios of choker setting, lateral yarding and yarding time showed high proportions of were shown that they were the highly in main operation time.

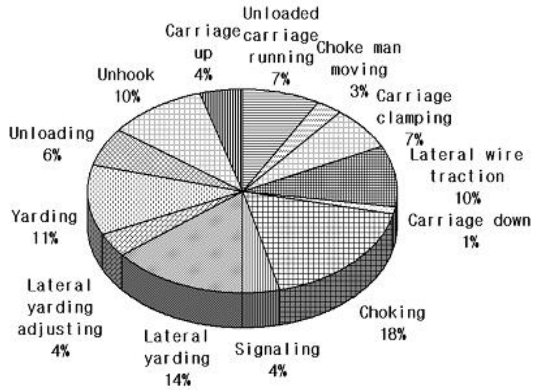

Figure 3. The component ratio of time elements in productive time

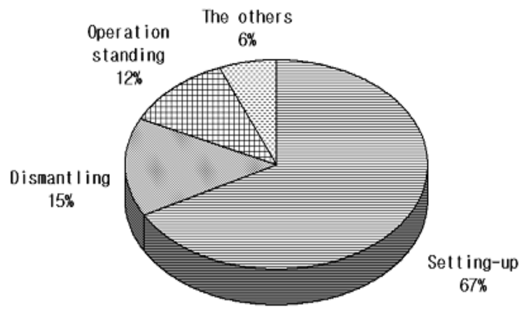

Figure 4. The component ratios of time element in non productive time

Table 2. Element operation time per one cycle in study site A.

Yarding time element		Element operation time	
		Time (sec.)	Ratio (%)
Main Operation	Unloaded carriage running	15.0	8.0
	Carriage down	2.1	1.1
	Choke man moving	5.4	2.9
	Carriage clamping	12.9	6.9
	Lateral wire traction	18.5	9.9
	Choking	33.0	17.6
	Signaling	6.9	3.7
	Lateral yarding	26.9	14.3
	Lateral yarding adjusting	7.3	3.9
	Yarding	20.8	11.1
	Unloading	11.6	6.2
	Unhook	19.1	10.2
	Carriage up	8.3	4.4
Total		187.8	100

Accessory Operation	Setting-up	2,389.0	81.1
	Dismantling	540.0	18.3
	Operation standing	11.9	0.4
	Others	6.3	0.2
Total		2,947.2	100

3.2 The efficiency analysis of yarding operation

In study area A of the maximum yarding distance of 100m and the lateral yarding distance of three planting rows in right and left side (i.e., the corridor width was total 7 planting rows), the productivity of the yarding operations in line thinning was shown in Table 3. An average volume of yarded timber per one day and a man was 5.25 m^3/man-day. This result showed about five times higher than the result of the existing study which was 1.03 m^3/man-day by manpower forwarding and 1.01 m^3/man-day by plastic log chute in the investigation location that average tree stock was 0.158 m^3/tree (Ma et al, 1997). Therefore, yarding operation in line thinning with a mobile tower-yarder was more efficient than other manual operations.

3.3 The simulation analysis of yarding operation time

The simulation analysis of yarding operation time is conducted using the data obtained in the study site A. The time element per one block calculated by the simulation analysis is shown in Table 4. Here, one block was 3 yarding lines of right and left yarded by one setting-up of a mobile tower-yarder in line thinning which was one line cutting and one line remaining (i.e., the total yarding width is 13 lines). The total yarding time per one block was 36,279 second (1 day 4 hours 39 second), and it was about 1 day 4 hours. And the simulation analysis for yarding operation finishing time per one hectare was conducted in the study site A. Here, one hectare was calculated to three blocks in the investigation location A. So, the total requirement time that was needed to finish the line thinning yarding operation for one hectare was 108,837 second (i.e., 5 days 13 minute 57 second) which was three times of the total yarding finishing time per one block, and the finishing time of line thinning yarding operation per one hectare by a mobile tower-yarder was about 5 day. This result was more high efficiency than the logging operation by manpower, wood grapple and tractor winch in Korea. Therefore, it was necessary to introduce the yarding operation system by a mobile tower-yarder (Park, 2004a).

Table 3. Operation efficiency by a mobile tower-yarder in study site A.

Items	Operation efficiency
The number of turns (cycles)	35
The extracted volume (m^3)	3.42
Yarding time (min)	120.2
Working crew (man)	2
Average turn volume (m^3/turn)	0.1
Cycle time (min/turn)	3.43
Average number of turn (turns/hr)	17.5
Hourly productivity (m^3/hr)	1.75
Daily productivity (m^3/man-day)	5.25

Note : Productive time per day was approximately 6 hours.

Table 4. Element operation time per one block by the simulation analysis.

Yarding time element		Time element	
		Time(sec)	Ratio(%)
Main operation	Unloaded carriage running	3,576	11.7
	Carriage down	323	1.1
	Choke man moving	832	2.7
	Carriage clamping	1,987	6.5
	Lateral wire traction	2,149	7.0
	Choking	5,082	16.6
	Signaling	1,063	3.5
	Lateral yarding	4,421	14.5
	Lateral yarding adjusting	1,124	3.7
	Yarding	3,985	13.1
	Unloading	1,786	5.8
	Unhook	2,941	9.6
	Carriage up	1,278	4.2
Total		30,547	100
Accessory operation	Setting-up	2,389	41.7
	Dismantling	540	9.4
	Operation standing	1,833	32.0
	The others	970	16.9
Total		5,732	100

3.4 An analysis of yarding operation system

1) Relationships between distance and pull out time in lateral wire rope traction

In the study site A and B, relationships between distance and time in the lateral wire rope traction are shown in Figure 5. In the study site A, it took less time to pull out the wire rope than study site B, because the pull out direction in A site was downward and it was easier and took less time.

2) Relationships between distance and time in the lateral yarding

In the study site A and B, relationships between distance and time in the lateral yarding are shown in Figure 6. In the study site A, lateral yarding speed was slower compared with site B because there was some delay or speed reduction due to hindrance of residual trees stand in study site A of line thinning yarding.

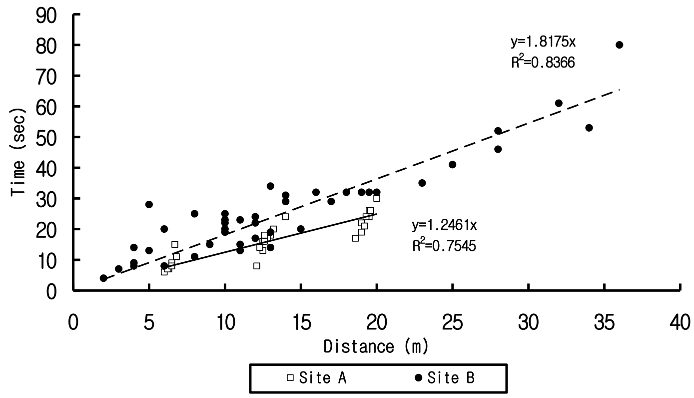

Figure 5. Relationships between distance and time in the lateral wire traction.

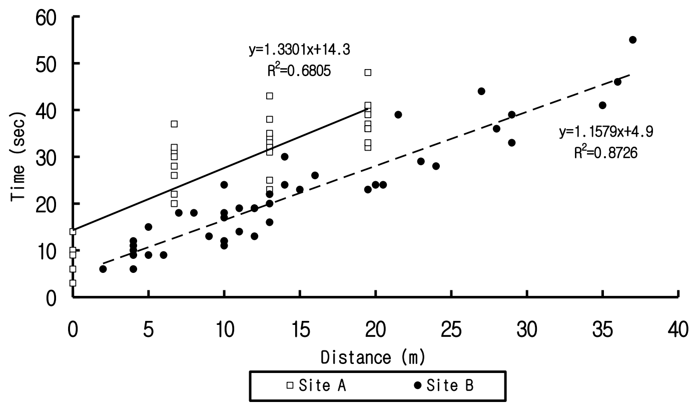

Figure 6. Relationships between distance and time in the lateral yarding.

3) Relationships between distance and inhaul time

In the study site A and B, relationships between distance and time in the yarding are shown in Figure 7. In the study site A, inhaul speed was faster than site B, while felled trees were small and yarding direction was uphill in site A of line thinning.

4) Relationships between lateral yarding distance and yarding cycle time

In the study site A and B, relationships between lateral distance and yarding cycle time for lateral yarding are shown in Figure 8. The study site A, was shown fast compared with B. This result will be because it took the various factors other than the lateral yarding distance in site A of line thinning yarding.

5) Relationships between distance and cycle time in the yarding

In the study site A and B, relationships between distance and cycle time in the yarding are shown in Figure 9. The study site A was shown fast compared with B. This result will be because it was easily to yard uphill direction and extraction subject were small trees in line thinning yarding.

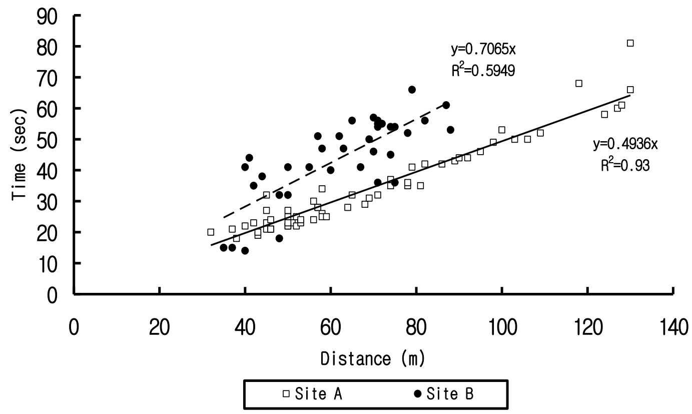

Figure 7. Relationships between distance and inhaul time.

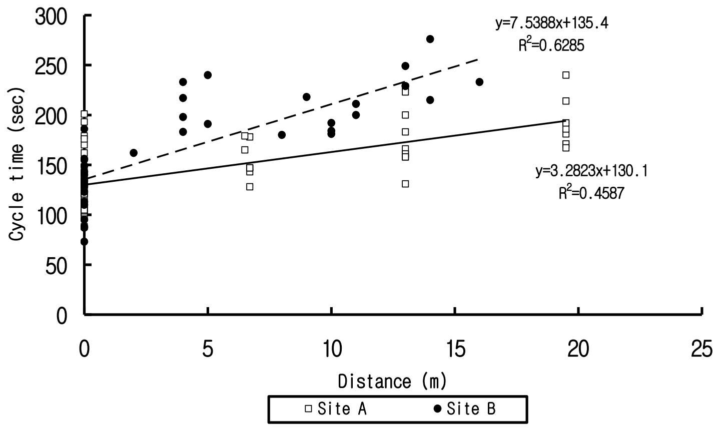

Figure 8. Relationships between distance and cycle time in the lateral yarding.

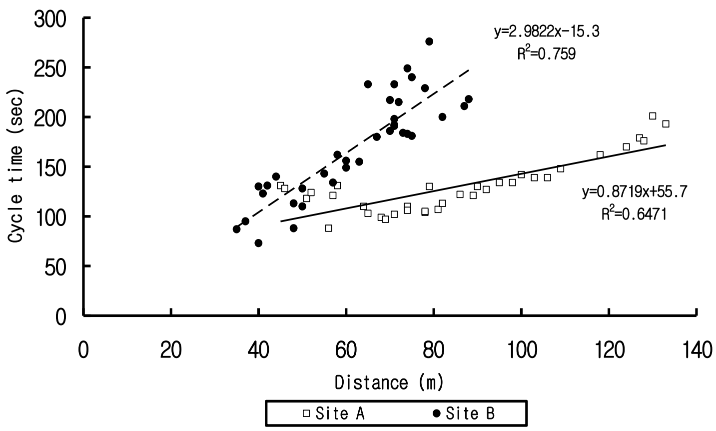

Figure 9. Relationships between distance and cycle time in the yarding.

3.5 The analysis of optimum lateral yarding distance and optimum setting-up spacing

The setting-up spacing of a mobile tower-yarder had an influence on the efficiency of yarding operation as most important factor. The setting-up spacing was two times of lateral yarding distance. So, the analysis of optimum lateral yarding distance for optimum setting-up spacing and was conducted using the data obtained in the study site A and B. The optimum lateral yarding distance was calculated using a formula presented in existing study (Kobayashi et al, 1992; Park, 1997; 2004b). Since optimum lateral yarding distance was obtained in relationships between lateral yarding distance and total yarding operation time, the results of optimum lateral yarding distance calculated was shown as Figure 10. The optimum lateral yarding distance calculated in the study site A and B was 9.5 m and 5.3 m, respectively. And the optimum setting-up spacing is 18.9 m and 10.5 m in the study site A and B. Therefore, the optimum setting-up spacing for the efficient yarding operation with a mobile tower-yarder in the condition site such as the study site A and B was about 20 m and 11 m.

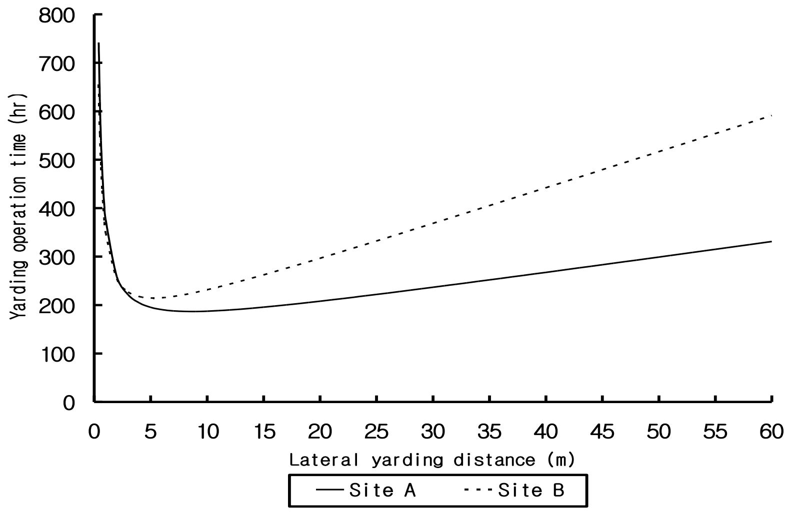

Figure 10. Relationships between lateral yarding distance and total yarding operation time.

4. CONCLUSIONS

This study was conducted to investigate the efficiency of yarding operation, the yarding operation system, the optimum lateral yarding distance and the optimum setting-up spacing in order to establish the optimum yarding operation system with a mobile tower-yarder in Korea.

As the results of this study, the ratio of choker setting time and lateral yarding time in the main operation time was the highest. An average yarding timber volume of the line thinning operation by a mobile tower-yarder was 5.25㎥per man-day. The yarding finishing time of 7 yarding lines of one block and 1 ha is about 1 day 4 hours and 5 days, respectively. And the optimum setting-up spacing was about 20 m and 11 m, respectively. Specially, the efficiency of yarding operation with a mobile tower-yarder was about five times higher than the result of the existing study which was 1.03 ㎥/nab-day by manpower forwarding and 1.01 ㎥/man-day by plastic log chute. And the yarding operation with a mobile tower-yarder was very efficient and environmentally friendly logging operation system. Therefore, it is necessary to introduce the yarding operation system by a mobile tower-yarder in Korea.

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An Evaluation on the Environmental Effects Induced by the Rock Blasting in Forest Road Construction at Rocky Areas in Turkey*

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Abstract
The history of contrasting modern forest road started more than fifty years ago in Turkey to opening up forest where located on hillside and at mountainous areas for management purposes. Angledozers and bulldozers have been used to construction of forest roads by this time. Because of the disadvantages' of these machines on environment or forest stand and the road construction techniques using these machines were left. Nowadays, excavator is newly used with these machines to construct the forest roads in view of its advantages.
In addition to that, to choose wrong and primitive rock blasting methods for mountainous or rocky areas cause irreparable damages both physical and biological on forest ecosystems.
In this study, the least harmful rock blasting designs were discussed by studying the road construction technique which is being used the primitive rock blasting methods to pass the rock on the road route and to reduce their effects on environment and forest stands in Turkey. Drilling, blasting designs and the possibility of environmental sensitive blasting methods were investigated on rocky forest areas.

Keywords: forest road construction, rock blasting, environmental effects, Turkey

1. INTRODUCTION

Forest engineering structures such as forest roads play an important role in forest management operations and forest development. They are complex engineering works which provide access to within the forests. They are not only essential for the extraction of wood and non-wood forest products but they provide overall access for forest management and monitoring purposes, and could also contribute to the overall rural infrastructure development or become part of the public road network. However if they are poorly planned and designed, constructed or maintained, forest roads can contribute significantly to environmental degradation. In fact, often inadequately engineered forest roads significantly contribute to increased water flows, sedimentation, soil erosion and, in the worst cases, land slips. Therefore, it is important that forest roads are designed and laid out by competent engineers who understand the need to minimize construction and maintenance costs, as well as soil disturbance (Heinrich 2001).

Overall demands for timber, terrain using of without planning, exceptional legal regulations in the forest law, and grazing caused to drawing of forests to mountainous terrain, where applying of forestry activities are heavy and quite costly in Turkey. Turkey has 20,7 million hectares forest which makes up 26,6 % of total forest land. The productive forest areas

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 273-281.*

are 10 547 987 hectares which makes up 51 % of the total forested areas (OGM, 2004). Approximately 46 % of the total forest areas are on steep land with slopes greater than 40 % (OÖİKR 2001).

The road needs of total forest area are calculated as 201 810 km in Turkey. At present, Turkey has 140 000 km forest roads which constructed in forest. Nevertheless forest opening is insufficient for rational forest management. Furthermore, in comparison with developed countries, road density is not satisfactory. On a total area of 10 547 987 of productive forests, the average forest opening was 13,27 m/ha, while for total forests and forest land it is 6,76 m/ha.

In addition to the existing forest road, it is stated that approximately 1 000 km forest road has been constructed in every year (OÖİKR 2001, OGM 2004). According to the OGM 2004 investment program (General Directorate of Forests Association), total forest road investment is 48.1 million (31,0 million $) and in this total road investment 10 million TL is allocated for 1000 km new road constructions . Generally, construction of each kilometer forest road costs 6451 $/km in Turkey.

In view of the forest road construction, the most expensive region of the Turkey is mountainous Eastern Black Sea Region. There are three regional forest enterprise named as Giresun, Trabzon and Artvin Forest District. Average forest road construction cost for three forests district is 13 000 $/km.

Mountainous areas are known as steep terrain areas and they have mostly rocky ground. The forest road construction is quite difficult and expensive in those rocky areas. It requires some special construction methods to pass the rocky areas (Acar 2005). One of the these construction methods is rock blasting. Blasting is a process where rock is to be broken into fragments with the use of explosive energy.

Choosing a wrong road route and primitive rock blasting methods for mountainous and rocky areas, results in physical and biological damage on forest ecosystems. Those effects may cause irreparable results. The main objectives of this study are to determine the road construction and rock blasting method with its environmental effects and to evaluate the rock blasting designs at forest road construction lasting in Black Sea Region of Turkey.

In a study conducted by USFWS (1993) it was stated that roads are one of the leading causes of habitat destruction and loss of connectivity throughout the world. One result of the regional scale fragmentation in the Northern Rockies is particularly evident with the current situation of the grizzly bear, which isolated in a handful of remnant isolated populations. The bear populations are centered in large, relatively undeveloped and undisturbed areas including the Greater Yellowstone Ecosystem, the Northern Continental Divide Ecosystem and, to a much lesser degree, in the mountains of northern Idaho and northwest Montana (USFWS 1993).

Persson et al. (1996) emphasized that, it is not possible to understand the economics of rock blasting in mining and construction engineering without reference to the economics of the production drillholes into which the explosive is loaded. The choice of explosive and the size of the most economic drillhole size and drilling depth is dictated by the cost of drilling. The cost of drilling depends on the penetration and wear characteristics of the rock material, and on the size and depth of the drillhole ((Persson, et al. 1996).

It is stated that in study that by taking into considerations the technical and economical aspects of blasting while an appropriate blasting designs are being done the ground vibration, air blast and the flying off the rock particles effecting forest life and environment should be controlled by planner. The peak particle velocity (PPV) (mm/s), the PPV-Displacement (mm), the PPV-Acceleration (mm/s2) and the frequency (Hz) should be measured and these should be controlled in limit that these parameters not give any damage on environment (Erçıktı 2004).

2. FOREST ROAD CONSTRUCTION PRACTICES IN TURKEY

General Directorate of Forests Association has been in charge of the forest managements and all the other activities in Turkey. In order to carry out these activities and arrivals to the forests (i.e. to open the forests for the management), the most important necessity is to construct some forest roads). Not only is a forest road an establishment which binds two places each other, but also it is an establishment which makes possible to benefit from all parts of going on activities in forests.

In practice, forest roads have been built according to principle of the written regulations named as 202 and additional instructions in Turkey. According to this guide, forest roads are classified as A and B types. This classification is made by taking into consideration of forest roads objectives and the timber amount which would be transported on these roads per year. Geometrical standards of forest roads in Turkey have given in Table 1 as briefly (OGM, 1984).

Table 1. Forest Road Types and Its Geometrical Specification

Forest Road Types	Main Forest Roads	Secondary Forest Roads	
		A-Type	B-Type
Road formation width (m)	7	6	4
Number of carriage-way	2	1	1
Maximum gradient (%)	8	10	12
Minimum curve radius (m)	50	35	10-12
Width of carriage-way (m)	3.5	3	4
Width of shoulders(m)	0.50	0.50	0.50
Width of ditch (m)	1.00	1.00	1.00
Width of Superstructure (m)	6	5	3

Generally the type of forest roads in Turkey is B- type whose platform and ditch widths are 4 m and 1m, respectively.

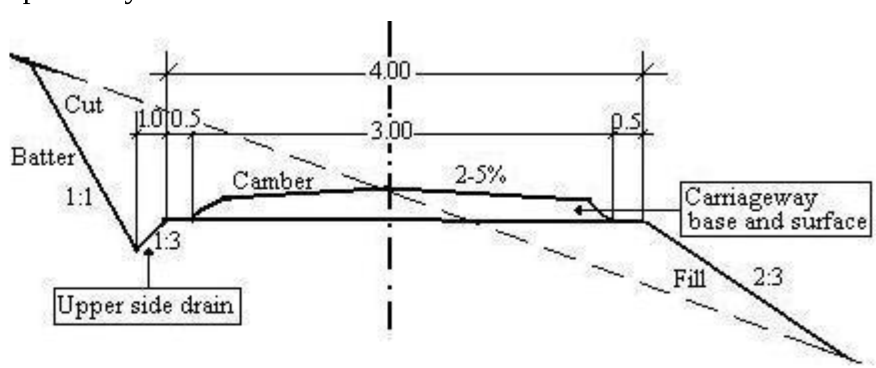

Figure 1: Typical Cross-Section of B-Type Secondary Forest Road

Generally, the forest road construction works are; the planning of the road on map, the application of the plan to the forest area, the excavation works and the building up the structure such as culvert, bridge, retaining wall, gabions etc. After the road route selection the forest road construction works are; road corridor preparation (clearing and felling the trees, etc), grubbing and stripping (removal of stumps, roots, topsoil and organic materials), disposal of slash and debris, subgrade construction (rock blasting and etc.), stabilizing the subgrade and surfacing the road.

Traditionally small or medium sized bulldozer and angle dozer have been used in the forest road constructions to decrease the road construction cost in Turkey. Although dozers usage to build the forest road seems cheaper and quicker than the other road construction machine alternatives at first sight, the usage of dozer for forest road construction is more expensive than the other alternatives because of their undesired impacts on environment and residual stands (Acar et al. 2005).

After that the excavated material is pushed to the downhill, it causes much damage on residual tree, sapling. In addition to these damages on stands, the excavated material covers the productive soil where can be cultivated. In order to meet the demands on environmental protection, hydraulic excavators have been employed in forest road construction recently; however, it has not been employed throughout Turkey yet (Acar et al. 2005).

3. ROCK EXCAVATION WORKS AND ROCK BLASTING

The dozers and the hydraulic excavators have been used to excavate the rocks on the forest road route in Turkey. Both the dozers and the excavators can excavate the sandy graveled soil, partially decomposed rock easily, but hard rocks can not be excavated by those machines economically in subgrade excavation phases of the road construction. Because of these reason, one of the economically excavation methods is the rock blasting.

Generally, blasting is a process where rock is broken into desired size with the use of explosive energy. Despite advancements in other rock breaking equipment, explosives still remain the cheapest method of rock breaking, although the process has many undesired environmental effects.

If there is any big and hard rock on the forest road route, the road construction works have been done in two phases in steep and rocky terrains in Turkey. The first one is blasting of the rock that was drilled by the drilling machines and the second one is smoothing of the blasted rock (Acar 1997). The first goal of the rock blasting is to break the rock that can be excavated by the vehicles such as dozer and excavator in its original place. To do effective and good blasting the structure and characteristics of rock that will be broken should be known.

In primitive rock blasting, the purpose may be simply to remove rock without respect for the size and shape of the broken rock. Growing concerns for the environment and a growing understanding of the economic usefulness of crushed rock for a ballast material, for road building, or for building construction generally dictate that the broken rock be cleared away to be used as fill material, or preferably as a raw material for building purposes. (Persson et al. 1996).

Because of this reasons; both economical, environmental sensitivity and the productivity of blasting should be taken into consideration while the rock blasting designs are being planned in the rock blasting on the forest road route. In this case, the rock can be broken at desired shape and the probable effects of blasting on forest or environment can be minimum level.

Especially in steep terrains and rocky areas in Turkey, contractors of road personal experiences and knowledge about rock that will be blasted have been used for the design of blasting method while forest roads are being built mostly (Figure 1). To increase of blasting productivity and to reduce environmental effects of blasting in rocky forest areas, all blasts must be properly designed and recorded for future reference.

Figure 2: Rock Drilling by Compressor on Forest Road Construction.

The explosives used in Turkish forest roads constructions have been produced by Machine Chemistry Industry Establishment (Makine Kimya Endüstrisi Kurumu (MKE)). These explosives are named as GOM, Jelatine and Antigrizu dynamites. Nevertheless, another explosive that have been used to blast the rock is named as Technical Ammonium Nitrate (TAN). The characteristics of TAN such; it is in powder form, has no water resistance, affected by moisture and includes nitroglycerin (OGM 1984).

Generally, holes have been drilled to the required depth to remove the rock, dynamites have been put in the bottom of holes and filled with Ammonium Nitrate Fuel Oil (ANFO) while the rock are being blasted. Nevertheless, the timing or delay capsules have not been used in the rock blasting in practice in Turkey. In fact, the timing or delay minimizes the pounds of explosive per delay period. This can significantly control noise and vibration effects.

The explosives not causing the fly-rock is more preferred than the explosives causing flying rock to excavate the rocks existing in forest roads route in rocky and steep slope terrain in Turkey (Acar and Şentürk, 1997). In choice of explosives, it is required that the blasted rock mass is controlled in road construction area (generally on an average wideness 20 m. road corridor) and the flying rocks not cause any damage on environment.

3.1. Environmental Effects of Rock Blasting

By using the explosives to break the rock mass existing in forest roads route, there are four different negative effects of blasting on environment. These effects are;

- Ground vibration,
- Air blast (air overpressure),

- The flying off the rock particles,
- Dust, poisonous gases and fumes emission (Nitromak 2004).

Especially, these problems are occurs on the field where uncontrolled blasting used for rock excavation. In some cases these environmental problems can be the some continual disagreement such as fear, complains etc. on inhabitants living the close to the blasting areas and these environmental problems give many damage on buildings.

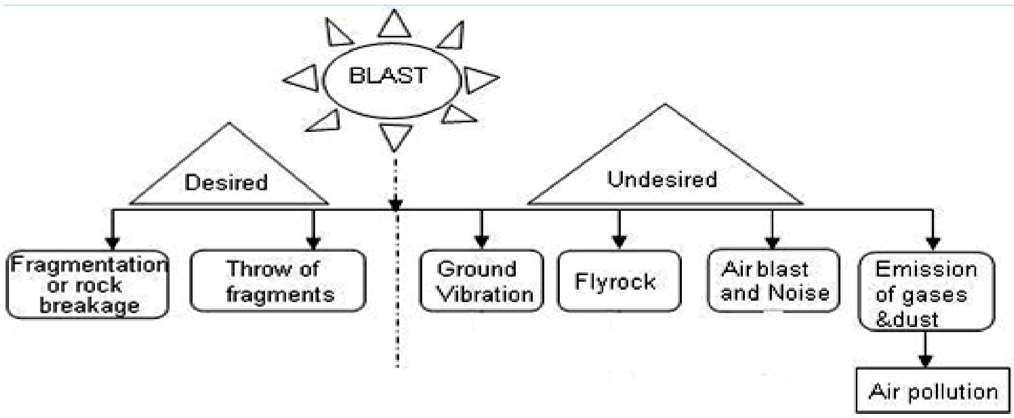

Figure 3: Desired and Undesired Effects of Rock Blasting (Reina et al. 2004)

The detonation of explosives for rock breakage induces a seismic disturbance which propagates in all directions from the explosion epicenter. Ground-borne vibrations from blasting are readily perceived in nearby residences and sometimes result in legal action alleging structural damage. However, in addition to the seismic disturbance, the detonation of explosives causes a transient pressure pulse which is propagated through the atmosphere. This phenomenon has been described in the literature as an air blast. Fly rock in rock blasting has been a series problem since blasting began several hundred years ago. Men have been killed; building, equipment, and material destroyed (Kaya 2004). The ground vibration may be cause of the avalanche in winter. These vibrations during periods of unusually wet soil conditions may lead to potential slope failures and it may start the landslide.

Between these problems, the most important problem of the forest road construction is the flying of the rock particles in rock blasting. Many disturbances come directly from flyrock effects in the rock blasting, such as:

- rocks embedded in trees, presenting hazards to fallers and mill workers,
- trees blown over or otherwise damaged by air blast and flyrock,
- carpeting of the forest floor with rock fragments, making reforestation difficult,
- pile-up of blasted rock against trees,
- physical damage to power lines or other structures,
- detrimental impacts to watercourses, creeks, or streams,
- rocks hung up on slopes, presenting hazards down slope (BCMF 2002).

It may be difficult to eliminate all flyrock from every blast because rock conditions and excavation requirements vary and can change frequently along the road location. Nevertheless, blasting crews and supervisors should be able to demonstrate that the practices they adopted were appropriate for the observed conditions, and that their practices were altered in subsequent blasts in response to changing rock conditions (BCMF 2002).

Figure 4: Drilling and Blasted Fly Rock Effects on Watercourse and Trees

As soon as the rock is blasted by using explosives intensive dust emission occurs. This dust sticks to forest tree leaves and other plant leaves. Dense dust on leaves plug the pores that help the photosynthesis and all of these affects the biological functions of the plants. In conclusion of this the dense dust affects the plant growth and it causes the volume loss. In addition to this, the dust disturbs the human near to the construction areas.

Especially, in steep terrain and rocky places, after the rock blasting the excavated materials are pushed to downhill by the dozers in Turkey. This material includes big sized rock and it damages on the tree and the sapling by striking, by breaking, peeling of the tree bark and injures of the tree bark and root. Serious quality loss become on the injured tree. Nevertheless, the injured trees are exposed by insects and fungus assaults and this threats the forest stand life.

The forest wildlife may be injured or disturbed by air blast, noise, flyrock and ground vibration. In this respect, air blast and ground vibration should be measured by a seismograph and these effects should be limited in appropriate level by taking into consideration the wild life and human discomfort.

4. CONCLUSION AND RECOMMENDATIONS

Turkey has steep terrain forests, and the roads have needed to be constructed by bulldozer and angle dozer. The forest road construction technologies are old and insensitive on environmental attention. Especially the design of blasting method does not care the environmental attentions in rocky terrain conditions. The ground vibration, air blast and the flying out the rock particles are affecting forest life and should be checked when the blasting design is done by planner. To reduce the environmental impacts of forest roads construction on stands, using the appropriate machine effecting at minimum level on stands such as excavator, choosing appropriate explosive and drilling-blasting techniques and certification should be taken into consideration.

The construction methods cause the loss of forest area and it gives great damages on soil, trees, sapling at the downslope of forest roads. This case is very important for the protection of forests from insect damages in sensitive areas and for the selection of wrong construction technique or rock drilling-blasting methods. These techniques and rock blasting methods should be more sensitive for the eastern Black Sea Region whose forest threatened by the insect recently.

In Turkey most forest road construction projects involve rock blasting which may involve great environmental challenges. To reduce these damages on stands and environmental and to decrease the economical loss it can be proposed as below:

- In practice, the usage of angle-dozers in the steep slope terrain and rocky places causes huge damages on downhill stands. To avoid the effects produced by this road constructions technique that causes damage on the stands, the modern, sensitive, controlled blasting technique and appropriate leveling methods should be used in forest road constructions.
- The hydraulic excavators (hammer) or the excavators that hydraulic drilling equipment should be used to construct the forest road, especially for sandy graveled soil and partially decomposed rocky areas.
- In order to carry out environmentally sound rock blasting, the possible damages from blasting should be determined with the local investigations of these damages, the optimal rock blasting designs for sensitive areas should be produced. Nevertheless, according to the determined criteria for rocky areas, the least harmful rock blasting designs should be created.
- The blaster and blasting consultant should arrange the geometry of the blast for optimal breakage. This is done so that the explosive pressure (P) and the moment (M) do not exceed the amount needed to break the rock. Excessive P and M causes 'Fly Rock' and excessive 'Air Blast' and 'Vibration' that can cause damage and injury.
- The timing or delay capsules have not been used in the rock blasting at forest road construction in Turkey. The timing or delay minimizes the pounds of explosive per delay period. This can significantly control noise and vibration effects.
- While the drilling-blasting designs are being done, the design variables of burden, stemming, subdrill, spacing, and timing should be selected to maximize fragmentation and to minimize excessive vibration, airblast, and fly rock.
- Blasters working in forest road construction should have a license and they should be certificated about rock blasting. After then blasters should be able to assess rock and site conditions, formulate appropriate blast designs, learn from previous results, and immediately revise field practices to reflect changing conditions.
- The drilling and blasting techniques to be used for forest road construction should minimize disturbance to forest resources and existing improvements and minimize the potential for landslides or slope instability.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

AmSteel Blue in Logging*

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Abstract
High strength synthetic ropes are an excellent candidate for wire replacement in logging application. These ropes have the equivalent strength of the same diameter wire rope but only one-seventh of the weight of wire. AmSteel Blue, a premium synthetic High Modulus Polyethylene (HMPE) rope developed by Samson, has already been used in various logging applications. This paper discusses the benefits to use synthetic ropes in logging, including ergonomics and safety considerations, efficiency improvement and cost reduction.

1. INTRODUCTION

There are 749 million acres of forest land in the United States split evenly east and west of the central plain of the country. The total forested land has grown 0.3% since 1997. Roughly 504 million acres (67%) of forest land is classified as timberland – land capable of producing in excess of 20 cubic feet of lumber per acre per year. 80% of pacific region forest land is classified as timberland.

Over the past 40 years the growing stock on timberland has increased substantially. Since 1953, timberland has increased 39% from 616 billion cubic feet of lumber to 856 billion cubic feet. The major increases in growing stock have occurred in the northern states (+96%) and south (+80%). Growing stock in the pacific coast region has declined due to the harvesting of older, higher volume stands and large areas of "set-asides" that are not available for logging. On a national basis, however, growing stock has exceeded harvesting for the past 40 years.

The logging industry makes extensive use of wire rope in harvesting operations. The wire is used above ground for lifting and transporting logs from the field to trucking operations. Wire is also used on the ground to hold and drag the logs. High strength synthetic ropes are an excellent wire replacement in various logging applications. These synthetic ropes have the equivalent strength of the same diameter wire rope but only one-seventh of the weight of wire. AmSteel Blue, a premium synthetic High Modulus Polyethylene (HMPE) rope developed by Samson, has already been successfully introduced and used in various logging applications.

2. AMSTEEL BLUE

In 1986, Samson pioneers use of High Modulus Polyethylene (HMPE) for a variety of Marine Applications to replace wire. The 2nd generation HMPE fiber, SK-75, became available in 1996 and Samson used it to create AmSteel Blue – a 12 strand HMPE rope.

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 97-105.*

AmSteel Blue was first introduced into the Commercial fishing industry and has been used successfully for over a decade in the following areas:

- Commercial Fishing
- Tree care
- Utility and power lines
- Fall Protection
- Entertainment Industry
- Mooring
- Tug

It is the primary wire replacement, based on its high strength, light weight and ease of repairability. Figure 1 Compares strength and weight between AmSteel and Wire cables. The size for size strengths compare with those of wire.

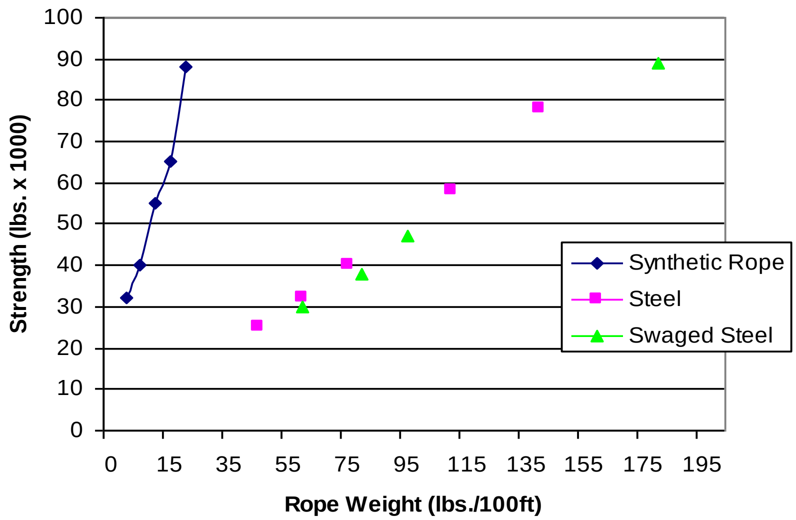

Figure 1. Strength and Weight comparison – AmSteel Blue vs. Steel

3. ADVANTAGE OF AMSTEEL BLUE OVER STEEL WIRE

- LIGHTWEIGHT,
  - Easy to pull to fallen logs, especially uphill
- FASTER CYCLE TIMES (time to get rope in place and return)
  - Means more production per operating hour!
- PHYSICALLY LESS STRENUOUS
  - Reduces fatigue build up, and associated aches and pains compared with steel wire rope. Less fatigue can reduce injuries and create safer operations.

- NO JAGGERS! (fish hooks)
  - No irritating lacerations and puncture wounds to the hands and arms.
- NO SNARLED WINCH DRUM WHEN WINCH IS SET TO FREE SPOOL:
  - Upon release of the drum to pull the line off, the torque tension stored in the spooled steel line creates a backlash similar to an open face fishing reel. These snarled spools frustrate operators and cause operational delays in pulling the line out to the logs.

- ELIMINATION OF THE DRAG ADJUSTMENT:
  - Used to limit snarling associated with coiled energy release and coil expansion of the steel wire rope. This is a benefit to the worker in reducing the force required to rotate the drum when pulling out the line.
- DIVING (line becoming buried between wraps on the drum).
  - On the rare occasion a synthetic line dives, it can easily be pulled free by hand. No need to use pry bars or hook the line to a fixed object (tree, stump) and pull the skidder ahead to pull the stuck line free off the unlocked spool.

- REDUCTION OF DELAYS
  - Equals more productive time.
- ABILITY TO LONG LINE SHORT CORNERS WITH SKIDDER (reach out to logs on a site typically harvested with cable yarding systems).
  - Saves time and expense of setting up a more expensive system. Typically, short corridors take longer to rig and de-rig than to yard the logs.
- ABILITY TO ACHIEVE DESIGNATED SKID TRAIL SPACING (trails for skidder to travel on instead of traveling all over the forest soils).
  - Reduces environmental impact of ground based skidding systems.

- SKIDDING EQUIPMENT CAN BE KEPT OUT OF RIPARIAN AREAS (stream sides) AND OTHER SENSITIVE SOIL SITES WHILE HARVESTING.
  - Using AmSteel-Blue allows logs from these areas to be winched and pulled further distances than steel wire rope.
- FEWER TRIPS BETWEEN RIGGING TREES.
  - All required lines and rigging can be moved in as few as one trip across the hillside.
- FASTER AND EASIER RIGGING OF TAIL AND INTERMEDIATE SUPPORT TREES.
  - Rigging straps and guylines can be attached to the climbing belt while on the ground, and raised with the climber during the climbing motion. This is not feasible with steel wire rope guylines. With steel guylines, a pass block would need to be raised, strapped to the tree, and then a pass rope used to hoist the steel guylines to get them to required attachment height.
- GUYLINES CAN BE RIGGED "TIGHTLY" BY ONE WORKER WITH A COME-ALONG. THERE IS LITTLE TO NO "BELLY" IN THE GUYLINE WHEN RIGGED.
  - Guyed trees are less likely to move compared to trees rigged with steel guylines when the skyline load is applied to the tail or intermediate lift trees because the slack has been removed from the line. Lighter AmSteel-Blue ropes have significantly less catenary effect (belly). Eyes with shackles meet most needs.

Fig. 3

Figure 3. Hooktender with rigging needed for a tail tree. The use of AmSteel-Blue ropes allows for all the rigging to be moved to the next tree in one trip with a pack frame or duffle bag. Shown are two 125-foot guylines, a rigging strap for hanging a block in the tree (block is in his hand), climbing belt and spurs, and a pass rope. Steel wire rope rigging would have required 2 or 3 trips to move to the next tree.

4. REPAIRABILITY OF AMSTEEL-BLUE:

The ease of splicing AmSteel-Blue 12-strand ropes permits easy and quick repairs to terminal ends, such as eyes, with the Buried Eye Splice. Additionally, repairs to inline sections of working lines may be performed as well with the End for End splice (Long Splice).

Repairs to AmSteel-Blue ropes or eyes should be performed when two or more strands have been severed. Repair of individual cut strands is not an approved practice. Repairing a single strand would also be more difficult and take longer than a complete rope splice repair.

A significant advantage with splicing of AmSteel-Blue ropes is the reduced length of the splice. The length of buried rope for each end of the End for End splice shown in Figure 2 is 4 feet to each side for the 3⁄4" AmSteel-Blue rope (3 fids lengths, 1 fid length = 16 inches). (One fid = 21 x rope diameter and each end of one buried tail = 63 x rope diameter). If this had been 3⁄4" steel wire rope, each end of rope to be tucked for the long splice would have been 15 feet. Thus, the total splice length for 3⁄4" rope is 8 feet for synthetic compared to 30 feet for steel!

Another particularly significant advantage with synthetic winch lines is the ability to splice additional length onto an existing line using the End for End splice as seen in Figure 4. The Long Splice is not done with steel wire rope winch lines. The spooled remaining good length of steel winch lines is removed and replaced with a new longer section.

Fig. 4

With practice, field personnel can become proficient with both Eye and End-for-End splices, even if they have no experience splicing wire rope. Splicing can be performed in the field with just a knife and a length of bailing wire. This can avoid downtime associated with getting repairs performed at rigging shops.

5. AMSTEEL BLUE IN LOGGING

AmSteel Blue can also be used in the following logging applications:

- Haywire / Strawline
- Guylines & Extensions
- Tree & Ground Straps
- Skidder Lines, Winch Lines
- Skyline Extensions
- Drop lines / Mainlines
- Chokers

Using Haywire as an example, AmSteel Blue provides the following benefits over wire

- Light weight – Faster to rig
- No need to carry heavy wire

- Run longer lengths without connecting sections
- Can be set-up on a winch and pulled off easily

Small diameter (1/4 to 3/8-inch) steel wire rope lines are used to rig larger steel lines on cable logging systems. These are known as haywire or straw lines. Most yarders contain a drum for spooling haywire. Additionally, coils of haywire are also used for laying out sections on the hillside. These coils are typically 200 feet in length, and weigh about 50 pounds each. The sections are connected to each other, to the haywire drum, and to the line to be pulled out. For example, to pull a 1-inch diameter skyline out 1000 feet, 2000 feet of haywire would need to be laid out: 1000 feet from the yarder to the tailhold, through a block, and then 1000 feet back to the yarder for connecting to the skyline. The haywire drum would then be spooled in, pulling the skyline out to the tailhold. AmSteel-Blue ropes are an ideal replacement for steel wire ropes in this application.

Fig. 5: AmSteel-Blue can reduce the weight of your haywire by 80%! This drastically reduces the time needed to rig the haywire.

6. COST ANALYSIS

A cost analysis is conducted to estimate the saving from using AmSteel vs. Wire cable, as Haywire, shown in Table 1.

The analysis is based on the assumption of using 5000 ft of 3/8" dia rope. Conservatively we estimate that the synthetic line last only half of the life of the wire.

Table 1. Haywire Cost Analysis – AmSteel Blue vs. Wire Cable

Haywire Cost Analysis - 5000 ft of 3/8" dia rope			
		AmSteel Blue	Wire Rope
Assumptions	Annual Layouts	500	500
	Estimated Life	**6 months**	**12 months**
Fixed cost	Total Weight of Haywire	**180 lb**	**1300 lb**
	Price of Rope per Foot, $/ft	$1.48	$1.00
	Total Haywire Price / Year	**$14,800**	**$5,000**
	Rope cost per operation	**$29.60**	**$10**
Variable cost	Man Hours per Layout	2 hour	8 hours
	Labor Rate/Hour - Hook Tender	$18	$18
	Downtime / Layout	0 hour	2 hours
	Labor Rate/Hour - Crew (average)	$15	$15
	Labor Cost / Layout	**$36**	**$174**
Summary	**Approximate Cost per Layout**	**$66**	**$184**
	Annual Operation Cost	**$32,800**	**$92,000**
	Annual Savings - (Per Haywire)	**$59,200**	
	Break-Even Life	**2 Months**	

Annual Savings - 25 Haywires **$1,480,000**

As the analysis shows, although AmSteel is more expensive than Wire rope, the operation cost with the synthetic rope is much lower than the wire cable. It only takes about 2 months to recover the investment of the synthetic lines. Furthermore, with more operations taking place, more saving is realized with AmSteel. For example, if an operation uses 25 Haywires the annual saving is about 1.5 million dollars.

7. SUMMARY

The main features and benefits of AmSteel Blue are listed in Table 2.

Table 2. Main Features and Benefits of AmSteel Blue

Features	Benefits vs. Wire
■ 15% of the weight of wire	■ Easier to handle
■ Will not kink	■ Fewer injuries
■ No jaggers	■ Less strain on workers
■ No Contamination from Lubricants	■ Better for the environment
■ High wear and flex fatigue life	■ Repair instead of replace
■ Weather resistant	■ Faster rigging
■ Chemical resistant	■ Easily Field Repaired
	■ Won't Rust
	■ Won't damage equipment

These features and benefits make Amsteel Blue a viable wire replacement offering lower operating costs in logging due to:

- Safety Improvement
  - Reduced health care costs
  - Less stress and strain on workers
  - Fewer injury claims
  - Less down time

- Efficiency Improvement
  - Reduced operations time
  - Reduced man hours per setup

ABOUT SAMSON

For well over 100 years, Samson has been recognized as a worldwide leader in the development and manufacture of high performance ropes. Among its many innovations, Samson invented the double braid and pioneered the first high modulus polyethylene fiber ropes. Today Samson engineers continue to pioneer the use of new fiber technology and the development of innovative coatings and constructions to produce ropes with unprecedented performance characteristics. Samson's research and development team is meeting an ever expanding market need for products with exceptional performance in critical applications. Samson is part of Wind River Holdings™ portfolio of operating companies.

2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Productivity and Cost of Processing and Top-skidding Long Logs*

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Abstract
The Forest Engineering Research Institute of Canada (FERIC) measured the productivity of two harvesters and a rubber tired grapple skidder operating in the southeastern Interior of British Columbia. The harvesters produced long logs at the stump and the skidder top-skidded the logs to roadside landings. FERIC assessed this long-log/top-skid harvest technique and compared its costs with those for tree-length/butt-skid systems that are more typically used.

Keywords: costs, productivity, harvesters, grapple skidders, top skidding, machine interaction

1. BACKGROUND

Tembec Industries Inc. in Cranbrook, BC operates several sawmills in the area as well as a pulp mill at Skookumchuck. Tembec's sawmills require long logs as their primary fibre source, and utilize short logs cut to a maximum 6.25 m (20'6") to supplement mill production.

Much of Tembec's wood supply is located on lower slopes of the Rocky Mountains, and frequently on slopes with grades from 20 to 60%. Historically, Tembec's contractors have dealt with the narrow valleys and steep slopes by using small landings – often oversized road turnouts built as part of the road system. Tembec has employed various systems on these sites including feller-bunchers with steep-slope capability, grapple skidders operating on skid trail networks, and processors stationed at roadside or on the small landings.

To try and improve overall production and reduce costs, Tembec has experimented with a variety of equipment configurations. On some sites, cut-to-length harvesters sometimes produced long logs that would then be handled by grapple skidders to roadside, and sometimes the harvester produced short logs that would then be handled by forwarders. In 2002, one trial involved grapple skidders to transport stems from a feller buncher to a dangle-head processor located on bladed skid trails. This system produced both long and short logs, which were then re-skidded downhill to landings for loading by a front-end loader. Tembec tested top-skidding and butt-skidding techniques with several of the equipment configurations.

Based on these experiences, Tembec staff drew several conclusions:

- Feller-processing long lengths was more productive than producing short lengths, since fewer cuts were made.
- Skidding was more productive than forwarding.
- Top skidding of long logs was more productive than butt-skidding because the skidder could collect a larger turn volume.

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 107-114.*

- Removing a dedicated processor from the conventional operation improved safety at the landing because only 3 machines (skidder, loader, truck) interacted instead of four.

In 2003, Tembec worked in partnership with one of its contractors to commit to a system that used a stump-area harvester to produce both long and short logs. A grapple skidder would then skid the piles of processed logs, by the top, downhill to the landing. Tembec requested that FERIC assess this long-log/top skid system and compare its performance to that of the tree-length/butt skid system.

2. OBJECTIVES

FERIC agreed on a project with the following objectives:

- Quantify harvester productivity for feller-processing long logs and compare the results to studies conducted for the ***INTERFACE*** [1] model.
- Assess length-measurement accuracy of the feller-processors.
- Quantify rubber-tired grapple skidder productivity when skidding bunches of logs by their tops.
- Assess machine interaction at the landing for long-log and tree-length systems.
- Assess and contrast productivity and cost for long-log and tree-length systems.

3. STUDY METHODS

FERIC conducted detailed-timing studies to assess productivity of the long-log system during the fall of 2003 and January 2004. The studies were on the felling-processing and skidding phases, and used the procedures FERIC employs to collect data for the ***INTERFACE*** model.

During January and February 2004, FERIC also performed shift-level monitoring of the long-log contractor and one of Tembec's conventional tree-length contractors. Harvesting machines were instrumented with Servis recorders and the operators provided daily charts and shift reports. The machines were monitored while each contractor harvested two small blocks. Production, obtained from Tembec's weigh scale records, totalled about 5100 m^3 for the long-log system and 6600 m^3 for the tree-length system. Working times were obtained from the charts and shift reports, and volumes were obtained by totalling the log loads delivered from each block as recorded in Tembec's weigh scale records.

3.1 Equipment and system descriptions

The equipment employed in the study is shown in Table 1.

Table 1. Equipment complement for each system

	Long-log/top-skid system	Tree-length/butt-skid system
Felling/feller-processor equipment	Caterpillar TK 722 harvester John Deere 2054 harvester each with Waratah HTH 20 head	John Deere 753 GL feller-buncher with Gilbert 22" head Case 9020 with Hultdins directional falling head
Skidders	John Deere 648 G III rubber-tired grapple skidder Caterpillar 517 tracked grapple skidder	Ranger H67 rubber-tired grapple skidder John Deere JD 650 G tracked line skidder
Processor	--	Linkbelt 2800 LX with Denharco 550 DH
Loader	John Deere 644 G front-end loader	None – trucks were self loaders

[1] *INTERFACE* is a model developed by FERIC to predict the costs for harvesting various harvest prescriptions using a variety of harvesting equipment. The software contains predefined rates of production as determined by previous and ongoing FERIC studies.

The harvesters normally produced four sorts. Products were separated according to whether they were redwood (Douglas fir and western larch) or whitewood (pine and spruce) species, and then further separated into short and long logs. The target length for the short log group was 6.25 m (20'6") and shorter lengths in 61 cm (2-foot) multiples were allowed. Long logs were defined as longer than 6.25 m and primarily comprised lengths from 11.4 m to 16.9 m in 61 cm multiples (37'6" and 55'6" in 2-foot multiples.) The four product sorts were stacked in separate piles in the stump area prior to skidding.

For the top-skid system, the long-log contractor used two skidders in a two-stage skidding process. First, the tracked Caterpillar 517 operated in the stump area in a "pre-skid bunching phase" in which the skidder operator first gathered and stacked the harvester log piles into larger bunches (Figure 1). It then forwarded the piles to a position on the primary skid trail. From there, the John Deere 648 top-skidded the large bunches the rest of the way to the landing (Figure 2).

Figure 1. Tracked skidder performing

Figure 2. Rubber-tired skidder

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 115-125.*

pre-skid bunching	arriving at landing

4. RESULTS AND DISCUSSION

4.1 Harvester productivity

FERIC studied the two harvesters for the long-log contractor in the fall and in the winter. Both operators were experienced. Table 2 shows some of the site conditions and results from the productivity studies. The table shows the block-average tree size from the cruise, but FERIC also measured the gross tree volume at the study sites within the blocks so that these studies could be compared with data from other FERIC studies.

Figure 3 shows harvester productivity from studies conducted by FERIC in western Canada for the ***INTERFACE*** model. The graph shows results for 37 studies of harvesters that produced short logs (<6.25 m in length) compared to five harvesters that produced long logs (McMorland 2003). The graph includes the four studies shown in Table 2. The long-log group comprised the three studies from Table 2 and two earlier studies on Tembec operations (McMorland 2003).

Table 2. Harvester productivity

	Fall 2003		January 2004	
	Block 052		Block 152	Block 37
	JD 2054	Cat 722	JD 2054	Cat 722
Cruise tree size, m³ (block average)	No cruise data		0.57	0.25 – 0.62
Silvicultural prescription	Reserve Douglas-fir, western larch (100 stems/ha)		Reserve Douglas-fir, western larch (30 stems/ha)	Reserve aspen & Douglas-fir, western larch (max 30 stems/ha)
Average slope at study site, %	21	15	38	7
No. of products [1]	2	4	4	4
Proportion of long logs, %	All short logs	90	60	86
Average gross stem volume in study, m³	0.34	0.28	0.51	0.40
Average stems / cycle (no.)	1.0	1.0	1.0	1.0
Average logs / stem (no.)	2.2	1.2	1.8	1.6
Average stems / PMH [2] (no.)	102	91	80	70
Average gross volume / PMH, m³	34.7	25.6	40.8	28.0

[1] Products were based on redwood and whitewood species species (Douglas fir and western larch vs. pine and spruce) and then length (short logs vs. long logs).
[2] PMH = Productive Machine Hours – the amount of time the machine was doing work related to its prime function; excludes delays >10 min.

The placement of the trend line for the long-log results suggests that harvester productivity was higher when the machines manufactured long logs. This may be true, but it is also visually apparent that the two sets of data overlap. The five observations for long logs may be too small a sample to represent a different data group.

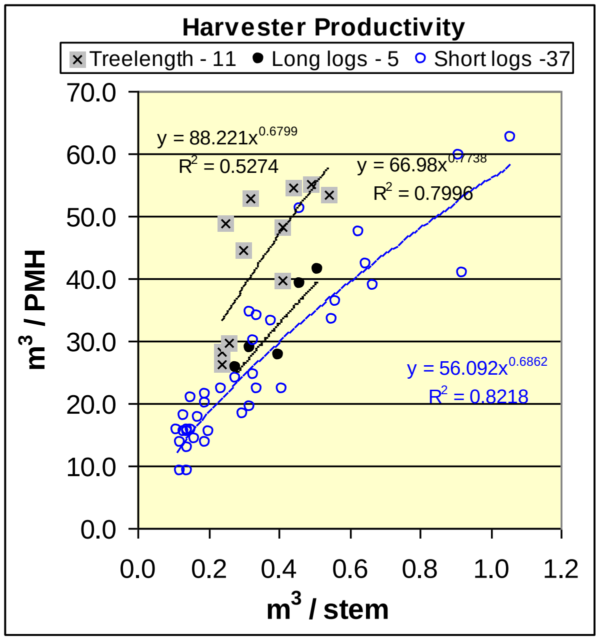

Figure 3. Harvester productivity for tree- length logs, long logs and short logs.

Figure 3 includes the results for 11 additional harvesters that produced tree-length logs (stems that were topped at maximum length after being measured). Harvesters in those studies operated similarly to stump-area delimbers, except that they made an accurate length measurement prior to topping. The trendline and data grouping for the tree-length results are markedly higher than the long-log and short-log results.

The following conclusions can be drawn from Figure 3.

- Harvesters that manufactured tree-length logs had higher hourly productivity than harvesters that produced shorter lengths.
- Harvesters that manufactured long logs (lengths between 12.2 and 18.3 m, or 40- and 60 feet) had slightly higher productivity than harvesters that produced logs less than or equal to 6.25 m long.
- In the tree-size range between 0.25 and 0.40 m^3/stem, hourly productivity can be similar for all three product groups.

4.2 Harvester length measurement accuracy

Table 3 summarizes the length assessment. Almost 80% of the logs were manufactured within the length tolerances allowed by Tembec. About 8% of logs were over length by an average of 3 cm, and 13% were under length by an average of nearly 10 cm. The under-length category was strongly influenced by one log that was 61 cm under the minimum and which accounted for almost half of the category length value. If this log was excluded from the assessment, the average under-length measure for the other 13 logs would have been 5.9 cm.

Table 3. Length measurement assessment

		Within tolerance	Under length	Over length
Short logs (<6.26m)	no. measured	15	3	0
	%	83	17	0
	average length under/over, cm	--	23.1	--
Long logs (>6.25)	no. measured	72	11	9
	%	78	12	10
	average length under/over, cm	--	6.2	3.1
All logs	no. measured	87	14	9
	%	79	13	8
	average length under/over, cm	--	9.8	3.1

4.3 Grapple skidder productivity

Examples of large turn volumes are shown in Figures 4 and 5. Turn volumes were consistently between 9.5 and 12.0 m^3 per turn, and averaged 11.4 m^3. The number of pieces per turn ranged from 10 to 53, and averaged 30.

The large turn volumes resulted in very high hourly volume production for the rubber-tired skidder. Figure 6 shows data from three top-skidding studies and 54 butt-skidding studies conducted by FERIC. A few of the studies were on adverse skids, but most of the machines skidded down favourable slopes.

Each data point is the average hourly productivity of one study. The top-skid data point at the 200-m class is from a Tembec contractor studied earlier as part of the INTERFACE program. This contractor also performed top skidding with a 115-kW class machine, but only conducted additional bunching on some of the turns.

Figure 4. End view of tops of a large top-skidded turn

Figure 5. Large-volume grapple skidder turn

The two data points at the 400-m distance class are the top-skidding studies from the John Deere 648 (115-kW size class) described in this report.[2] These two studies show hourly volume production of approximately 70 m^3 per Productive Machine Hour (PMH). These results are higher than the productivities found in other skidder studies at this distance, likely because bunches were made larger by additional bunching

The butt-skidding studies were conducted on rubber-tired machines in the 115 kW, 125 kW and 135 kW engine-size classes. Roughly, these groups correspond to 160, 170 and 180 hp engine-size classes. About half of the studies were with 115 kW machines, one-third were with 125 kW machines and the remainder were with the 135 kW class.

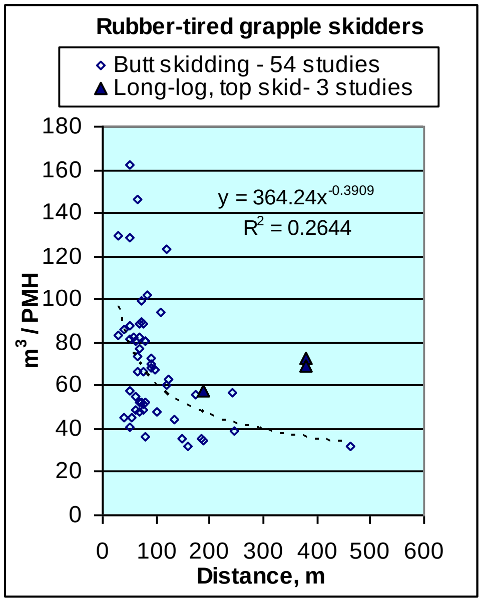

Figure 6. Skidder productivity.

[2] Other common models in the in the 115-kW size-class include the Timberjack 460D, Ranger 667, and Cat 525B.

Top skidding is often considered inappropriate because of unacceptable levels of wood breakage. FERIC did not observe any breakage as a result of top skidding during these studies. Figures 2, 4 and 5 show that tops of top-skidded bunched logs are packed together and tightly grasped. The logs tend to support each other, resulting in turns that are less susceptible to bending than turns that are top-skidded by the comparatively flimsy stem leader.

4.4 Machine interaction at roadside for long-log and tree-length systems

Table 4 shows the results of the machine interaction studies. The table lists the percentage of time that different numbers of machines were active on the landing. FERIC studied a tree-length contractor in this assessment (System B in Table 4) in order to include a conventional contractor with a front-end loader. Observations were recorded at 5-minute intervals for one shift at each operation, starting around 7:00 am and finishing between 3:30 and 4:00 pm.

Table 4. Percentage of time machine interaction occurred

	Long-log / top skid	Tree-length / butt skid	
Equipment type	2 skidders 1 front-end loader	**System A** 2 skidders 1 processor	**System B** 2 skidders ½ time front-end loader ½ time processor
Landing empty, %	2	0	2
1 harvest machine, %	74	57	65
2 harvest machines, %	22	29	31
3 harvest machines, %	2	14	2
Trucks present on landing, %	58	20	33

The long-log / top skid system resulted in less harvest machine interaction at the landing. Only one harvest machine was active at the landing for 74% of the time, compared to 57% and 65% of the time for the tree-length systems. Although reducing the amount of interaction does not guarantee that there will be fewer safety incidents, certainly the risk of an incident is reduced.

4.5 Productivity and cost for long-log and tree-length systems

Productivity

FERIC collected shift-level data at the long-log and tree-length contractors' operations as each harvested two small blocks**.** Table 5 presents the block descriptions.

Table 5. Block descriptions for winter blocks

Harvest system	Prescription	Gross volume (m3/ha)	Gross merchantable tree size, m3	Species Distribution Lodgepole pine %	Western larch %	Douglas-fir %	Spruce %
Long-log / top-skid							
Block 152	Reserve D-fir/larch (30 stems/ha)	303	0.57	77	2	15	6
Block 037	Reserve aspen, D-fir (max 30 stems/ha)	372	0.62	80	7	3	10
Tree-length / butt skid							
Block 12	Reserve larch >25 cm (10 stems/ha)	288	0.21	92	6	2	--
Block 13	Reserve non-lodgepole pine >18 cm	279	0.32	92	6	2	--

The long-log blocks had a greater volume/ha and larger average stem size than the tree-length areas. The topography was generally similar in that the harvest blocks were on 20-30% slopes, but the treelength block had some trails with 55-m segments of 15% adverse grades. Occasional short pitches of adverse skidding in the long-log blocks ranged from 8% to 27% and accounted for about 5% of skid distance. Average skid distance was approximately 170 m at the tree-length operation and 380 m in the long-log blocks.

Costs The two harvesters used by the contractor in the long-log block did not have identical scheduling or productivity. The on-board computers could not be used to apportion production between the machines because one of the computers was not operating correctly.

For costing purposes, the harvesters' results have been combined to derive a weighted average hourly cost. Table 6 shows the production and working hours for both harvesters, their hourly costs, and the weighted combined cost.

Table 6. Weighted hourly cost for harvesters in long-log blocks [a]

	Harvester 1 Caterpillar TK 722	Harvester 2 John Deere 2054	Combined	Weighted Average, $ / SMH
Number of shifts	9.5	8.5	18.0	
Productive machine hours (PMH)	91.8	80.4	172.2	
Delay, h	10.8	8.9	19.7	
Scheduled machine hours (SMH)	102.67	89.25	**191.9**	
Machine cost, $ / SMH	197.33	160.64		
Cost, $	20,259	14,337	34,596	**180.27**

[a] Note that "long-log" is a descriptor used to differentiate from tree-length operations. The long-log harvesting system produces a small percentage of short logs.

Table 7 shows the cost comparison between the two systems. The weighted hourly volume for the harvesters was 26.4 m^3/SMH, meaning that each harvester produced roughly at that rate. The long-log/top-skid combination was estimated to be $2.92/$m^3$ less expensive to employ than the more conventional tree-length/butt skid system.

Most of the savings for the long-log system occurred because the harvester had a "one-step-to-product" cost of $6.82/$m^3$ compared to the "two-step-to-product" cost of $10.53/$m^3$ for the buncher/processor system. Some of the savings is a result of productivity differences between the two systems due to differences in average stem size (larger at the long-log operation). However, the skidding phase cost for the long-log system was also lower even though two skidding machines were utilized and skid distances were considerably longer. The lower skidding cost was the result of the large top-skidded turn volumes.

As noted, the long-log/top skid operation had a larger average stem size compared to the butt-skid operation. A smaller stem size probably would not alter direct skidding productivity at this operation – turn volumes would be unlikely to change because turns are composed of logs, not stems – but the pre-skid cost may increase to reflect more accumulation time necessary for large turn volumes.

The front-end loader was not instrumented with a recording device so net productive time was not measured. The loader was required on site earlier each day than the other harvesting machines in order to load early trucks, and it stayed until the end of the working day with the other machines to organize the landing and log decks for the next morning. This resulted in more scheduled time/day for the loader than for the other machines.

Table 7. Productivity and cost comparison

	Shifts (no)	Productive Machine Hours (PMH)	Delays (h)	Scheduled Machine Hours (SMH)	Utilization (%)	Machine Cost a ($/SMH)	Volume (m3/SMH)	Cost ($/m3)
Long-log/top-skid b								
Harvesters	18	172.2	19.7	191.9	90	180.27	26.4	6.82
Pre-skid	8	79.4	8.6	88.0	90	140.09	57.7	2.43
Skidder	8	76.5	10.5.	87.0	88	113.04	58.3	1.94

Front-end loader	8			104.0		89.00	48.8	1.82
Total								13.01
Tree-length/butt-skid c								
Buncher	24	180.6	28.3	208.9	86	146.06	31.8	4.60
Skidder	32	261.7	24.8	286.5	91	112.82	23.2	4.87
Processor	28	203.9	58.0	261.9	78	150.34	25.4	5.92
Miscellaneous d				43.1				0.54
Total								15.94

[a] These costs are based on FERIC's standard costing methodology for determining machine and operating costs. These costs do not include supervision, profit, or overhead and are not the actual costs incurred by the contractor or company.
[b] Total volume produced was 5074 m3
[c] Total volume produced was 6640 m3
[d] Occasional tracked cable skidder and feller-director

5. CONCLUSIONS / IMPLEMENTATION

Harvesters that manufactured tree-length logs had higher hourly productivity than harvesters that produced shorter lengths. Harvesters that manufactured long logs between 12.2 and 18.3 m (40 and 60 feet) had slightly higher productivity than harvesters that produced logs less than or equal to 6.25 m long. In the tree-size range between 0.25 and 0.40 m^3/stem, hourly productivity can be similar for all three product groups.

Most of the logs were manufactured within the length tolerances allowed by Tembec.

Skidder turn volumes when top-skidded were consistently between 9.5 and 12.0 m^3 per turn because bunches were made larger by additional gathering and bunching at the stump area. This resulted in a very high hourly volume production of approximately 70 m^3/PMH at an average skid distance of about 400 m. These results were higher than those found in other skidder studies, regardless of machine size.

FERIC did not observe any breakage as a result of top skidding during these studies.

The long-log / top skid system is potentially safer because it resulted in less harvest machine interaction at the landing. As well, the long-log/top-skid combination was estimated to be $2.92 less expensive per m^3 to employ than the more conventional tree-length/butt skid system. Most of the savings for the long-log system occurred because the harvester had a "one-step-to-product" cost of \$6.82/m^3 compared to the "two-step-to-product" cost of \$10.53/m^3 for the buncher/processor system. Skidding cost for the long-log system was also lower, even though two skidding machines were utilized and the skid distances were considerably longer. The lower cost was the result of the large top-skidded turn volumes.

Although outside the scope of this study, there are additional benefits from using a long-log/top skid system:

- reduced regeneration costs / higher survival rates (increased moisture retention and less grass at the stump area)
- savings in landing construction
- reduction or elimination of slash disposal
- safety hazard avoidance / reduced cost of accidents

6. ACKNOWLEDGEMENTS

The author thanks the staff at Tembec Industries Inc., Norm Roberts Logging and Crabbe Logging for their help in setting up and conducting this study. In addition, thanks to FERIC staff Joanne Lennerton and Pat Forrester for help with field work and analysis, and Marv Clark, Tony Sauder, Yvonne Chu and Shelley Kerr for valuable input to the report.

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Productivity and cost of cut-to-length and whole-tree harvesting in mixed-conifer stand in northern Idaho*

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Abstract
Among the modern mechanized harvesting methods, the most commonly used are cut-to-length (CTL) and whole-tree (WT) harvesting. Cost differences between CTL and WT harvesting are generally acknowledged, but the degree of difference varies widely because of variations in stand and harvesting attributes. In this study, harvesting productivity, cost (stump-to-truck), and log value recovery were evaluated and compared between CTL and WT harvesting working side-by-side in two different mixed-conifer stands in northern Idaho. Each site included two replications of each of the harvesting options. Hourly productivity ranged from 1,163 to 5,428 ft^3 per productive machine hour (PMH) and 1,350 to 6,552 ft^3/PMH for CTL and WT harvesting machines, respectively. This result suggests that the WT harvesting system completes harvesting work faster than CTL harvesting due to the specific task assigned to each machine. CTL harvesting system costs were \$0.34/ft^3 and \$0.36/ft^3 while WT harvesting costs were \$0.22/ ft^3 and \$0.33/ft^3 in Princeton and Deary sites, respectively. Higher productivity of the WT harvesting system resulted in lower harvesting costs, although hourly machine rates for the WT harvesting system was slightly higher than for the CTL harvesting system. Harvesting costs (\$/ft^3) were highly influenced by trail distance (skidding/forwarding distance), log length and diameter, and machine combinations. WT harvesting recovered more sawlog and pulpwood volume but less ton-wood volume than CTL harvesting. Sawlog volume represented over 70% of the total harvest volume of WT harvesting. Consequently, the net revenue from WT harvesting was higher than CTL harvesting.

Keywords: mechanized harvesting, ground-based system, productivity equations, logging cost, product recovery.

1. INTRODUCTION

Timber harvesting is an essential tool for forestland management. It is used for wood production, wildlife habitat management, and to reduce fuel build up and the associated wildfire risk in the forest. Harvesting systems and methods used for the harvesting activities such as felling, processing, primary transportation to the landing, loading, and log transportation to the mill greatly affect overall harvesting cost, productivity (volume of logs produced per hour during a harvesting operation), overall profitability of harvesting operations, and returns to a landowner

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 127-136.*

(Han *et al.* 2004). Factors such as tree size, operator skill and motivation, undergrowth density, and silvicultural prescription also affect productivity and cost (Yaoxiang *et al.* 2006).

Currently, about 55% of the world's wood harvest is performed manually with a chainsaw while the remaining 45% is harvested mechanically. Of the mechanically harvested portion, about 65% is harvested using the WT method and the remaining 35% using the CTL method (Ponsse 2005).

In the Pacific northwest, CTL harvesting systems have been increasingly used for thinning on gentle terrain because they handle small-diameter trees very efficiently, provide a safer, enclosed working environment, and consistently produce high-quality end products at a reasonable cost (Kellogg *et al.* 1992). In CTL harvesting, harvester is used to process (delimbing and bucking) at the stump area. A forwarder then transports the logs from the stump area to the landing (central log collection area in the forest). The forwarder is also generally used to load logs onto the trucks. A typical mechanized WT requires four machines; feller-buncher, skidder, processor, and loader. The feller-buncher fells and aggregates trees, the skidder drags a bunch of trees to the landing, while the processor delimbs and buck trees at the landing.

Harvesting productivity and cost between CTL and WT harvesting is different. In a simulation study generated for three Appalachian hardwood stand, WT harvesting produced 22,153 ft^3 per week, while CTL harvesting's weekly production averaged 8,423 ft^3 (Yaoxiang *et al.* 2006). The higher productivity of WT harvesting was due to specific task of each harvesting machines.

A cost-efficient harvesting operation improves profitability in timber production and overall competitiveness of the timber production sector (Efthymiou 2001). In some earlier studies, CTL harvesting costs were often comparable to or lower than WT harvesting costs (Lanford and Stokes 1996). In contrast, two other studies found the CTL harvesting to be 15 to 30% more expensive than WT harvesting (Gingras 1996; Gingras and Favreau 1996). In these studies, harvesting cost differences was primarily affected by trail distance.

One of the objectives in timber harvesting is to maximize revenue while controlling cost through high value recovery (Murphy *et al.* 1996). Value recovery is a process whereby stems are cut into logs according to pre-determined specifications with the goal of obtaining the highest possible value (Ian *et al*. 2004).

Much is known about harvesting productivity and how harvesting and stand variables affect operational efficiency of mechanized harvesting systems (Kellogg *et al.* 1992), but there are still discrepancies in results with respect to cost differences between CTL and WT harvesting. Potential revenue between these two harvesting methods may be different since each method produces different log products. This study was designed to broaden our knowledge of harvesting productivity, cost, and log value recovery through a side-by-side comparison between CTL and WT harvesting.

2. METHOD

2.1 Study site and system description

The study sites were located in Princeton and Deary, Latah County, northern Idaho. The two sites are composed of Douglas-fir (*Psuedotsuga menziesii*), grand fir (*Abies grandis*), lodgepole pine (*Pinus contorta*), ponderosa pine (*Pinus ponderosa*), western larch (*Larix occidentalis*), white pine (*Pinus strobes*), and red cedar (*Genus lumis*). The stand in Princeton is a 22-acre unit with average tree diameter at breast height (DBH) of 11 in., ground slope range from 3 to 34%, and tree age from 35 to 80 years old. The Deary stand is a 48.1-acre stand with average tree DBH of 11 in., ground slope range from 2 to 32%, and tree age from 70 to 130 years.

Each site was divided into four sub-units and allocated at random to CTL and WT harvesting. Before harvesting, 14 sample plots in each unit were laid out to collect pre-harvesting stand inventory data. In each plot, tree height and DBH were measured to estimate basal area per acre, trees per acre, and total tree volume. Our experimental design showed similarities in stand and ground conditions between the CTL and WT harvesting units in each location (Table 1). There was no significant difference in mean DBH between the CTL and WT harvesting sites in Princeton and Deary ($p < 0.05$).

Table 1. Descriptions of stand characteristics in Princeton and Deary

Characteristics	Princeton		Deary	
	CTL	WT	CTL	WT
Total area (ac.)	8.2	9.3	22.0	26.1
Average DBH (in.)	11.0	11.0	11.5	11.0
Average height (ft)	66.0	70.0	67.0	68.0
Average basal area (ft^2/ac.)	169.2	126.2	116.0	117.0
Trees per acre	191.0	181.0	191.0	176.0
Harvest volume (MBF[1]/ac.)	14.4	12.0	13.3	14.2
Species composition (%)				
Douglas-fir	39	25	27	31
grand fir	25	20	30	50
lodgepole pine	14	21	42	15
ponderosa pine	4	2	0	0
red cedar	11	27	1	4
western larch	6	5	0	0
white pine	1	0	0	0

[1]thousand board feet

2.2 Harvesting systems and operations

In Princeton site, CTL harvesting operations used a single-grip harvester (Valmet 500T) machine to fell and process trees for two days prior to the forwarding operation. This was done for safety reasons and to provide sufficient logs to keep the forwarder machine (Valmet 890T, with a squirt boom loader) productive throughout the harvesting operation. The forwarding operation was uphill at an average distance of 406 ft. A Prentice 410DX loader was used for loading logs on the truck. For the WT harvesting operation, a continuous disc-saw feller-buncher (Timco 455EXL) was used to fell trees for two days prior to skidding of trees by a crawler (CAT D-518). Direction of skidding operation was uphill, at an average skidding distance of 426 ft. A grapple-processor (CAT) and a Link-Belt 240LX log loader were used for tree processing and log loading, respectively.

In CTL harvesting at the Deary site, the same model of harvester and forwarder were used, but with different operators. Forwarding was downhill at an average forwarding distance of 919 ft. For the WT harvesting system, a bar-saw feller-buncher (Timco Hydro Buncher T435) was used to fell trees three days prior to primary transportation (skidding) of trees by crawler (CAT D-518). Direction of skidding operation was downhill, at an average skidding distance of 626 ft. A stroke-boom delimber (PC200 Komatsu) and a log loader (PC220 Komatsu) were used for processing and loading, respectively.

Hourly machine cost as measured in dollar per scheduled machine hours ($/SMH)) was estimated using standard machine rate calculation practices (Miyata 1980). New machine prices were collected from dealers and contractors in northern Idaho. Estimated economic life for all machines was five years with 1,800 working hours per year. Salvage value was set at 20%, interest rate at 8%, insurance at 1%, and taxes at 1.5%; operator wage at $22.00 per hour plus 32% benefits. Hourly fuel consumption was estimated based on machine transmission; percentage utilization, and maintenance and repair cost was estimated based on a previous study (Brinker *et al.* 2002). The resulting hourly costs for the equipment are shown in Table 2. Hourly machine costs ($/SMH) of CTL harvesting systems were slightly higher than those in WT harvesting systems.

Table 2. Hourly cost ($/SMH[1]) for harvesting system and equipment

Site	CTL				WT				
Location	Harvester	Forwarder	Loader	Total	Feller-buncher	Crawler	Processor	Loader	Total
	($/SMH)				($/SMH)				
Princeton	138.4	143.3	81.2	362.9	110.3	108.8	107.7	91.6	418.4
Deary	138.4	143.3	143.3	425.0	99.2	108.8	131.2	90.8	430.0

[1]scheduled machine hour based on utilization rates for each machine: 65% for harvester, forwarder, crawler, feller-buncher, and 50% for loader (Brinker *et al.* 2002).

2.3 Data collection and analysis

Time study using a stopwatch technique was conducted to collect harvesting productivity data and to establish relationships between cycle times, load size, and stand variables. Harvester and feller-buncher operations were evaluated based on 1000 pre-marked trees (500 trees in each unit) to determine tree size distribution data of the stand. Each marked tree was numbered and correlated to specific data on DBH and species. This way, accurate tree size and species data was collected while observing harvesting operations at a safe distance. The numbering method was also combined with ocular observations during harvesting to collect additional data, as visibility of numbers on tree stems was sometimes difficult.

Before skidding operations on the WT units, landing locations and major skid trails were identified by the crawler operator. Distances of tree bunches to the landing were measured with a tape and recorded on stumps, logs, and residual trees. The marked distances on stumps, logs, and residual trees represent travel distances to each bunch when the crawler machine transports the bunch to the landing. Distances to new a bunch further away from the initial marked distances was based on a previously marked distance to a reference point plus a new distance measured from the marked distances to the new bunch location.

Prior to forwarder machine activity, the harvester creates forwarder trails by felling and processing every tree within and around its path. Each forwarder trail was divided into short distances of 50 to 100 ft. The short interval distances were measured and recorded on stumps, logs, and residual trees. These numbers were observed and distances between those marked were estimated at some safe distance from active forwarding operations.

The tree size and number of logs manufactured in each processor cycle were collected by ocular estimation of DBH and count of logs produced per tree. The number of pieces per loader cycle was also collected by ocular count of logs during loading into the truck.

Time study data collected from the field was examined for normality and outliers and was used to develop predictive equations by running an ordinary least squares regression procedure in SAS software (SAS 1999). Independent variables such as DBH, travel distance, and number of logs or trees, were related to each cycle time measured in centi-minutes.

Harvesting productivity was determined using productivity equations developed for cycle time and production in volume of recovered sawlog (large-end diameter > 8 in.), ton-wood (large-end diameter range 5 to 8 in., and top minimum diameter of 4 in.), and pulpwood (any dead dry log, decay logs, and logs below specified mill lengths). Average piece volume of sawlog, pulpwood, and ton-wood was estimated from log weight data collected at the mills. Each truck load volume was converted to cubit foot (ft^3) and board feet (bf) log volume using U.S. Forest Service method (((Total log weight per truck load)/2000)/56.7 ft^3/ton x (4.75 bf/ft^3)) (Henry 2002).

3. RESULTS AND DISCUSSION

3.1 Harvesting productivity

The results of delay-free productivity (ft^3/productive machine hour (PMH)) are presented for the CTL and WT harvesting machines in Table 3. At the Princeton site, the CTL harvester had the highest productivity of 1,762 ft^3/PMH compared to forwarder's low productivity of 1,483 ft^3/PMH. Delay-free productivity of the harvester was comparable to productivity levels of single-grip harvesters reported elsewhere (LeDoux and Huyler 2001). Of the WT harvesting machines, the feller-buncher had the highest productivity of 6,552 ft^3/PMH, while the least productivity was recorded for crawler machine.

At the Deary site, the highest productivity of 5,428 ft^3/PMH was recorded for log loading operation using CTL harvesting forwarder. Of the WT harvesting machines, the loader had the highest productivity of 3,351 ft^3/PMH compared to crawler lowest productivity of 1,350 ft^3/PMH. The forwarder and crawler productivities recorded in this study are within productivity ranges reported in previous studies (Lanford and Stoke 1996; David e*t al.* 2005).

The results from the two sites consistently showed higher productivity for WT harvesting machines than for CTL harvesting machines as observed in previous studies (Andersson 1994; Yaoxiang *et al.* 2006). Higher productivity of the WT harvesting was as a result of designated task for each machine. For example crawler productivity as measured in ft^3/PMH was higher than forwarder at both the Princeton and Deary sites due to short cycle time. The crawler only travels loaded with trees often times without intermediate stops before unloading trees at the landing. In contrast, the forwarder had a longer cycle time because it travels a longer distance with regular intermediate stops to sort and load logs into its bunk. Trail distance was found to be the primary factor, affecting crawler and forwarder productivity as suggested in other studies (Kellogg and Spong 2004).

3.2 Harvesting cost

The stump-to-truck cost for CTL harvesting was $0.34/ft^3 and $0.36/ft^3, while WT harvesting cost was $0.22/ft^3 and $0.33/ft^3 in Princeton and Deary respectively (Table 3). Primary transportation cost of trees/logs from the stump area to landing by forwarder and crawler machines accounted for the greater proportion of total harvesting cost of CTL and WT harvesting in the two study sites.

Table 3. Stump-to-truck cost ($/ft^3) of cut-to-length and whole-tree harvesting

	Machine cost ($/PMH[1])	Hourly production (ft^3/PMH)	Harvesting cost ($/ft^3)	Percentage (%) A	B
Princeton					
CTL: Harvester	197.83	1,762	0.11	34	
Forwarder	220.49	1,483	0.15	45	
Loader	162.43	2,333	0.07	21	
Total	580.75		0.34	100	
WT: Feller-buncher[3]	169.68	6,552	0.03	14	
Crawler	167.45	2,060	0.08	36	
Processor	165.63	2,824	0.06	27	
Loader	183.20	3,673	0.05	23	
Total	685.95		0.22	100	33.3
Deary					
CTL: Harvester	197.83	1,610	0.12	35	
Forwarder	220.49	1,163	0.19	54	
Loader[2]	220.49	5,428	0.04	11	
Total	638.81		0.36	100	
WT: Feller-buncher[4]	152.60	2,745	0.06	18	
Crawler	167.45	1,350	0.12	36	
Processor	200.04	1,983	0.10	30	
Loader	183.66	3,351	0.05	15	
Total	714.26		0.33	100	8.3

[1]productive machine hour; [2]forwarder machine used for loading log truck; [3]continuous disc-saw feller-buncher; [4]bar-saw feller-buncher; A-percentage cost of CTL and WT harvesting machines; B-percentage cost difference over WT harvesting.

CTL harvesting cost was 33.3% and 8.3% more expensive than WT harvesting in Princeton and Deary respectively. These differences are primarily due to differences in forwarder and crawler operating cost in transportation of trees/logs from the stump to landing. The cost of operating a crawler is less expansive than a forwarder machine because the purchasing price and all associated ownership cost of a crawler machine was about 24% less than a forwarder machine, and also more productive. On the average, the crawler produced 2,060 ft^3/PMH (28% more than forwarder productivity in Princeton site) and 1,350 ft^3/PMH (14% more than forwarder productivity in Deary site) due to its short delay-free cycle time.

The higher percentage difference (33.3%) over WT harvesting in Princeton harvesting operations can be explained on differences in machine combinations and productivity. In Princeton and Deary sites, similar forwarder and harvester models were used, thus resulting to a minimum variation in CTL harvesting machine productivity between the two sites. In contrast, all WT harvesting machines used at Princeton site were significantly more productive than the set of machines used in Deary site. For example bar-saw feller-buncher used in Deary site was less productive than the continuous disc-saw feller-buncher used in Princeton site. Delay-free cycle time for continuous disc-saw feller-buncher was about half the delay-free cycle time of bar-saw feller-buncher with correspondingly high productivity due to saw type together with machine design elements that allows for high-speed rotation of the saw.

3.3 Harvesting productivity equations

Productivity equations were developed for all harvesting machines from the detailed time study, using independent variables of trail distance, DBH, and number of trees/logs (Table 4).

Table 4. Delay-free cycle time equations for cut-to-length and whole tree harvesting machines

Site/Machines	Average cycle time estimator (centi-min.)	r^2		f-value	p-value	n
Princeton		Training[3]	Validated[4]			
CTL: Harvester	$30.04 + 0.20DBH^2 + 8.30LOG$	0.31	0.13	14.19	0.0003	450
Forwarder	599.89 + 1.35TED – 0.064ITD + 1.26TLD + 9.63 PIECE	0.73	0.50	23.20	0.0001	35
WT: Feller-buncher	$18.22 + 0.037DBH^2$	0.16	0.27	1.88	0.7450	350
Crawler	192.85 - 0.181TED + 0.87TLD - 3.092TREE	0.61	0.60	57.22	0.0001	133
Processor	$Ln^{2.81 + 0.064DBH + 0.27LOG}$	0.66	0.66	225.50	0.0001	224
Deary CTL: Harvester	$27.63 + 0.48\ DBH^2 + 1.05LOG$	0.45	0.16	45.00	0.0001	450
Forwarder	634.44 + 0.640TED + 0.427TLD + 0.640ITD + 11.87PIECE	0.83	0.72	58.45	0.0001	60
WT: Feller-buncher	29.32 + 0.77DBH + 1.769DISTANCE	0.64	0.42	103.10	0.0001	297
Crawler	$399.31 + 0.00046TLD^2 + 0.000015TED^2 + 4.29TREE$	0.75	0.76	180.30	0.0001	314
Processor	0.43 + 3.34DBH + 34.02LOG	0.54	0.39	137.00	0.0001	181
Loader	1882 + 8.362PIECE	0.15	ND	2.30	0.1410	26
Combined						
CTL: Harvester	33.30 + 0.069DBH + 0.11LOG - 0.16DIRECT	0.40	0.10	15.30	0.0001	900
Forwarder	318.81 + 0.954TED + 0.559ITD + 0.44TLD + 11.04PIECE + 380.79DIRECT	0.74	0.65	42.70	0.0001	97
WT: Feller-buncher	3.58 + 0.024DBH - 0.80SAW	0.51	0.04	9.83	0.0019	394
Crawler	199.11 + 0.87TED + 0.65TLD + 6.24TREE +11.07DIRECT	0.68	0.78	201.00	0.0001	62

TED -travel empty distance measured from the landing; ITD-interval travel distance traveled by forwarder while picking logs; TLD-distance traveled with full load of trees or logs; DBH-diameter at breast height; PIECE- # logs pieces carried per trip; TREE- # trees being carried per trip; DIRECT “ 1” if it was uphill skidding or forwarding “ 0” otherwise; SAW “ 1” if continuous disc-saw was used, “ 0” otherwise; [3]r^2 developed from 70% of observed data; [4]r^2 produced from using productivity equations to predict reserved data. ND-no data for validation

Productivity equations developed for all harvesting machines have significant f-value ($p<0.0001$) except for feller-buncher ($p<0.7450$) and loader ($p<0.1410$) machines used in Princeton and Deary, respectively. The significance of the f-value indicated that the developed productivity equations are better predictors of average cycle time than using the observed average cycle time values. The training r^2 (r^2 developed from 70% of observed data) for all productivity equations were within the range of r^2 values of previously developed productivity equation (Kellogg *et al.* 2004; Yaoxiang 2006). A test of the adequacy of the productivity equations is shown in the values of validated r^2 (r^2 produced from using developed productivity equations to predict 30% of observed data not used for developing productivity equations). A minimal difference between training r^2 and validated r^2 indicates that the productivity equation can predict average delay-free cycle time with minimum variance. This outcome suggests that productivity equations developed for forwarder, crawler, and processor are good predictors of harvesting productivity and thus can be used to predict harvesting productivity in stands with similar characteristics.

3.4 Harvest volume and log value recovery

In the two study sites, WT harvesting recovered more sawlog volume but less ton-wood volume than CTL harvesting (Table 5). CTL harvesting recovered more ton-wood than WT harvesting because it handled small-diameter stems efficiently (Kellogg *et al*.1992).

Harvested sawlog volume of CTL harvesting was comparable to WT harvesting sawlog volume in Deary site. This comparable volume between CTL and WT harvesting is consistent with those observed in a previous study (Young and Hynes 1996).

Table 5. Total harvest volume and revenue from cut-to-length and whole-tree harvesting

Site and Product	Product volume recovery					Value recovery	
	CTL	WT	CTL	WT	Difference	CTL	WT
	---------(ft^3/ac.)---------		-----(MBF[1]/ac.)-------		(%)	--------($/ac.)------	
Princeton							
Sawlog	1,674	1,662	6.8	7.9	13.9[5]	3,290	3,572
Ton-wood	383	282	-	-	26[6]	450	360
Deary							
Sawlog[2]	1,455	1,663	7.4	7.5	1.3[5]	3,196	3,713
Ton-wood[3]	327	281	-	-	14[6]	432	369
Pulpwood[4]	376	382	-	-	2[6]	286	291

[1]thousand board feet; [2]a log of large-end diameter greater than 8 in.; [3]a log of large-end diameter range from 5 to 8 in. and top minimum diameter of 4 in.; [4]any snag, decay log and logs below specified mill lengths; [5]sawlog difference based on MBF/ac.; [6]ton-wood and sawlog difference based on ft^3/ac.

The higher sawlog volume recovered by WT harvesting may be due to differences in manufactured log lengths. Although the contractors who operated in these sites were not given the freedom to produce diverse products. However, WT harvesting recovered every possible volume by manufacturing diverse log lengths ranging from 15.5 ft to 35 ft. In addition, tree found with DBH greater than 22 in. in the CTL harvesting site were not included in total sawlog volume presented because the harvester could not handle such tree sizes.

Delivered log price at mills in northern Idaho were $470MBF, $45/ton, and $26/ton for sawlog, ton-wood, and pulpwood respectively. When all product values are considered, the WT system generated slightly higher returns from the products at both study sites. Assuming that ton-wood volume constituted a greater proportion of total harvest volume in this study, CTL harvesting return would be higher than WT harvesting.

4. CONCLUSION

Cost differences between CTL and WT harvesting may range from 8.3 to 33.3% depending on average trail distance, machine combinations, and individual machine productivity. Primary transportation cost (stump-to-landing) was the highest cost in each harvesting system, and caused cost differences between CTL and WT harvesting. Primary transportation costs accounted for 45 to 54% and 35 to 36% of the total CTL and WT harvesting cost respectively. In addition, WT harvesting was less expensive than CTL harvesting due to the higher productivity of individual machines because of designated task for each WT harvesting machine. Combination of highly productive WT harvesting machines as shown in Princeton harvesting operations resulted in a more cost-effective harvesting operation than CTL harvesting.

CTL harvesting recovered more ton-wood but less sawlog volume per acre than WT harvesting on the two study sites. Sawlog volume represented over 70% of total harvest volume of WT harvesting. Consequently, the net revenue from WT harvesting was higher than CTL harvesting.

Our study indicated that WT harvesting was a more productive and cost-effective system compared to CTL harvesting, but that differences between these systems are highly sensitive to harvesting and stand variables. In view of these outcomes, a further research is necessary to explore the effect of other variables not considered in this study such as effect of other machine combinations (e.g. grapple skidder) and silvicultural prescriptions on cost, productivity, and log value recovery of CTL and WT harvesting.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Mastication: A fuel reduction and site preperation alternative*

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Abstract
During the fall of 2005, a study was conducted at Priest River Experimental Forest (PREF) in northern Idaho to investigate the economics of mastication used to treat activity and standing live fuels. In this study, a rotary head masticator was used to crush and chop activity fuels within harvest units on 37.07 acres. Production averaged 0.57 acres/hour (range 0.21-0.89 ac/hr). Costs average $530 per acre (range $335-$1395 per acre). Additionally, eleven fireline segments totaling 2326 feet were constructed through activity fuels using the same mastication machine. On average, 18 ft of fuelbreak was created through mastication (range 16-23 feet) combined with 4 ft of fireline (range 3-5 feet) with 100 percent mineral soil exposure constructed down the center of the trail. Total debris (including activity fuels) ranged from 26-61 tons per acre with production averaging 6.9 feet per minute (range 3.1-9.1 feet). This manuscript, concentrates on cost-analysis concerning mastication and it has shown that stand and site characteristics such as slope, residual tree density, and total acreage can significantly affect the time required to treat these areas. This research as it progresses will provide data on cost-benefit analyses comparing mastication, prescribed fire, and grapple piling/burning site preparation and fuel treatment alternatives.

Keywords: mastication, activity fuels, fuel treatments, site preparation

1. INTRODUCTION

Fuels (slash) created through harvest or fuel reduction treatments most often are treated to reduce fire risk and/or prepare sites for the establishment, growth, and survival of new seedlings (Eramian & Neuenschwander 1989, Graham et al. 2005, Graham et al. 1989). Treating activity fuels and preparing sites for planting can be conducted through the use of machines, prescribed fire, and/or chemicals (Graham et al. 2005). In nearly all settings, better seedling establishment and growth is achieved when site preparation is properly applied, thereby providing greater economic returns compared to settings in which sites are not prepared (Graham et al. 2005, Hawkins et al. 2006).

In the Western United States, prescribed fire has been extensively used for fuel reduction and site preparation. The use of fire can be relatively inexpensive compared to other methods, especially as the size of the treatment unit increases and fixed expenses can be distributed over more acres (Cleaves & Brodie 1990). Properly applied prescribed fire can decrease hazard fuels and remove undesirable ground-level vegetation without the need for extensive manual labor.

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 137-146.*

Another popular alternative is slash piling where crawler tractors with rakes or grapple machines pile slash followed by burning. Both prescribed fire and piling, use fire to consume the material which is becoming increasingly difficult and expensive to utilize, especially near populated areas. Air quality from smoke and the chance of a fire escaping, as well as an increased presence of wildland urban structures are just a few of the concerns associated with fire use (Berry and Hesseln 2004, Shindler and Reed 1996). Moreover, prescribed fire and/or piling of slash may not be an option depending on residual tree species, which are not resistant to fire (grand fir (*Abies grandis*), western white pine (*Pinus monticola*), lodgepole pine (*Pinus contorta*), western redcedar (*Thuja plicata*) or other physical constraints (e.g. slope angle and residual stand structure) which may preclude piling of slash.

Mechanical mastication of fuels often is an alternative to both prescribed fire and piling. Mastication involves reducing the size of forest vegetation and downed material by grinding, shredding, chunking or chopping material. Initial studies have shown mastication can effectively crunch or masticate fuels created by harvest or be used to remove standing live or dead trees (Graham and Jain, 2005). Mastication can also be used to increase the distance between the base of tree canopies and the soil surface, as well as increase wood decomposition rates by insuring wood is in contact with the soil surface (Edmonds and Mara 1998; Forest Service 2005).

In order to realize the physical and biological benefits of site preparation and fuel reduction their costs need to be considered; however, limited cost evaluations of mastication are available. Moreover, what information is available lacks factors such as the influence of slope or amount of material either in the residual overstory or the amount of fuels. Both of these factors can have a major influence on the overall cost of mastication. Rummer et. al (2003) provide estimates (across all forest types in the United States) of $35-$300 per acre for prescribed fire and $100-$1000 per acre for mastication. The Dry Forest Mechanized Fuels Treatment Trials Project (Coulter et al. 2002) observed several machines masticating standing vegetation and woody material during fuel treatment and found average costs ranging from $400 to $850 per acre. The USDA Forest Service, Bonners Ferry Ranger District in northern Idaho recently estimated between $255-$400 per acre for a mini-excavator to grapple pile slash, $85-$140 per acre to burn piles, and $175 per acre for a hand crew to slash undesirable standing vegetation resulting in a total of $505-715 per acre (Wynsma 2006). In all these estimates and reports, there was very little information on the circumstances in which the individual factors (slope, residual tree density, and amount of slash to be treated) may affect the overall cost of mastication.

Information is needed on equipment limitations and production implications due to slope, residual stand density, and the amount of activity fuel to be masticated. The objective of this study was to begin evaluating different masticators, starting with a rotary head mastication machine. We investigated the cost of masticating activity fuels and determined how site (slope) and stand variables affected treatment costs. In addition, we evaluated the effectiveness and performance using a masticator to construct fireline.

2. METHODS

2.1 Study Site

A multidisciplinary study in western hemlock (*Tsuga heterophylla*) forests is located on the USDA Forest Service, Rocky Mountain Research Station, Priest River Experimental Forest (PREF) located in northern Idaho. The silvicultural objective of the study is to develop innovative silvicultural techniques that increase the forests resiliency to wildfire, disease, and insects. In addition a suite of various treatments are being tested which involve free selection (harvest), herringbone landscape patterns to decrease landscape fire risk, alternative fuel and site preparation treatments, natural and artificial regeneration of early- and late-seral species, and the evaluation of these treatments on decomposition. Slopes range from 25 to 50 percent, and unit size, species composition, and distribution of residual overstory varies. Moreover, various amounts of small material remain that requires slashing (e.g., lopping, falling). After harvest, the amount of activity fuels ranged from 24-54 tons per acre. Of the 24 units involved in the study, 10 units were masticated, 7 units will be grapple piled, and 7 units are to have prescribed fire. A cost analysis will be conducted on all units, however; only the mastication has been completed.

2.2 Study Design

Ten mastication study sites totaling 37.07 acres were established. Several of these units were further subdivided when mastication commenced to further stratify the units to capture variation in operating environments such as the number and juxtaposition of residual trees, structure composition, and amount of activity fuels; thus creating 19 study units (Table 1). The objective of the mastication was to create chunks (1 to 3 feet long) and insure the debris and needles and leaves were in contact with the soil surface. The masticator was also used to slash undesirable trees that remained standing after harvest.

2.3 Mastication Machine

A rotary mastication head was used during this study. The base machine was a 161 hp Caterpillar model 322B forest machine (FM) excavator/log loader weighing ≈80,000 lbs including the mastication head. Using the contractor's specifications, we estimated the ground pressure to be around 8 pounds per square inch (psi). In order to minimize soil compaction, the machine traveled across an area once while masticating up to a 70-foot wide strip. The FM has a ground clearance of 27 inches and an increased hydraulic motor capacity needed to turn 26 inch single grousered tracks (compared to triple grousers found on most excavators). The machine was modified to allow operation on steep slopes (> 45%) and includes larger oil pans, and a five point seatbelt used to firmly hold the operator in the seat to reduce fatigue. The overall width of the machine was 11.5 feet. The mastication head designed by the contractor weighed 6,200 lbs and had a 48 inch cutting surface. A hydraulic clamp, often referred to as a thumb, was integrated into the head design. With this thumb, the operator could grab and move material. An auxiliary 125 hp diesel engine mounted on the base machine powered an additional hydraulic system providing power for the mastication head. The hourly machine rate for this study was $300/hr, including the operator's wage and a dedicated shop truck.

2.4 Data Collection

Plots were established to quantify post harvest fuel amounts, residual trees, and soil surface conditions. Slash mastication and fire line construction occurred during the later half of September 2005. Elemental time and motion studies were conducted during machine operation. Unit starting and ending times were noted and using three stopwatches total time spent masticating standing vegetation (live), traveling (not masticating), and any delays were recorded. Mastication of fuels were acquired by subtracting recorded elements from the total unit mastication time. All delays were measured and categorized as either operational, mechanical, personal, or administrative. Unit areas were measured using a Trimble GeoExplorer XT GPS unit and Pathfinder office software. Fireline segment lengths were measured using a stringbox hipchain. A photographic fuel estimate series (Morgan and Shiplett 1989) was used to estimate tons/acre of woody debris on firelines. Total time to construct fireline segments were noted and recorded using a stopwatch.

Data were transferred to computer using the Microsoft Excel program. Linear regression was performed using statistical analysis software (SPSS) to create a predictive delay-free production cycle model. Independent variables are considered highly significant when the P-value < 0.05.

3. RESULTS AND DISCUSSION

3.1 Mastication

A total of 65.34 hours of mastication occurred during this study. Nineteen units were masticated totaling 37.07 acres. Table 1 details machine activity observed for each unit treated. The machine operator was moderately experienced. Early observations indicated that the operator frequently moved the machine short distances without treating slash but this non-productive machine movement decreased as the study progressed. Overall, downed fuels were treated 80% of the time, moving without mastication occurred 12%, while 8% of the time was divided equally between masticating standing live vegetation and delays (totals, table 1).

Table 1. Observed machine activity time (centi-minutes) listed from highest to least productive

Unit	Move within unit (no mastication)	Cut standing (live)	Masticate	Delays	Total time	Acres
8-D	30.79	12.28	254.18	7.75	**305**	**4.03**
12-B	5.92	2.08	63.20	4.80	**76**	**0.91**
8-B	37.08	30.27	299.90	2.75	**370**	**4.03**
14-A	17.68	2.10	104.22	0.00	**124**	**1.39**
8-C	6.17	8.28	111.55	3.00	**129**	**1.42**
12-A	22.95	2.55	100.87	21.63	**148**	**1.61**
8-A	46.63	22.20	327.43	13.74	**410**	**4.46**
10	28.73	3.25	190.02	0.00	**222**	**2.20**
4-B	11.72	1.40	163.83	3.05	**180**	**1.70**
23-B	27.17	9.83	93.03	2.97	**133**	**1.18**
9-B	61.47	20.27	248.52	56.75	**387**	**3.28**
23-A	41.68	7.77	161.50	10.05	**221**	**1.81**
7-A	27.97	0.37	288.16	1.51	**318**	**2.60**
4-A	26.55	2.48	245.87	9.09	**284**	**2.19**
15	35.18	23.07	170.38	1.37	**230**	**1.77**
9-A	12.93	2.15	127.51	3.41	**146**	**1.09**
14-B	16.00	3.83	59.43	11.39	**91**	**0.67**
7-B	5.95	0.00	74.05	0.00	**80**	**0.49**
16-A	1.87	7.13	58.00	0.00	**67**	**0.24**
Totals	**464 (12%)**	**161 (4%)**	**3142 (80%)**	**153 (4%)**	**3921 (100%)**	**37.07**

Large fuels (> 3 inches diameter) were reduced on all units (Table 2). This large diameter material consisting of broken logs, long butts, tops and limbs were often converted to smaller chunks and wood pieces thereby increasing the amount of small (<3 inch) debris on most units (Table 2). Total fuel loadings (tons/acre) were reduced by mastication on 63% of the units as exemplified by the units in which the amount of fine fuels were decreased (negative values <3 inch ,Table 2). It is likely that these fine fuels were widely dispersed or incorporated into the soil surface since no fuels were removed from the site.

The machine treated an average 0.57 acres/hour with an average cost of $530 per acre (Table 2). Treating slash on steep slopes resulted in the highest cost per acre ($1396). Operating on such slopes required additional care by the operator to maintain machine stability slowing production. Working near standing trees appeared to slow production most likely by preventing the operator from freely swinging the boom. In addition the operator needed to ensure that standing trees were not damaged inadvertently by the head or by the base machine. As such additional time was required to treat these areas. During the coarse of the fuel treatments the operator controlled what live vegetation to cut and how the fuels were treated; often however, an onsite forest administrator directed the operator to "jackpot masticate" some fuels or otherwise direct the mastication operation. During such operations areas with large amounts of fuels were targeted while areas with small amounts received no treatment.

Table 2. Activity fuels treatment productivity listed from lowest to highest costs ($/acre)

		Post-treatment						
Unit	Pre-treatment tons/acre	Change in >3 inch material	Change in <3 inch material	Residual trees/acre	Slope (%)	Area (acres)	Production (ac/hr)	Costs ($/ac)
8-D	34.2	-54%	54%	3	32	4.03	0.79	$ 378
12-B	37.1	-32%	175%	3	32	0.91	0.72	$ 418
8-B	20.8	-32%	124%	1	32	4.03	0.70	$ 426
14-A	47.2	-23%	150%	1	35	1.39	0.67	$ 446
8-C	18.8	-64%	27%	2	32	1.42	0.66	$ 454
12-A	39.1	-51%	110%	4	32	1.61	0.65	$ 460
8-A	24.0	-41%	92%	2	32	4.46	0.65	$ 460
10	34.9	-23%	54%	2	27	2.20	0.59	$ 505
4-B	27.6	-37%	66%	5	31	1.70	0.57	$ 529
23-B	50.9	-63%	(-4)%	20	24	1.18	0.53	$ 564
9-B	57.8	-65%	90%	6	45	3.28	0.51	$ 590
23-A	50.9	-63%	(-4)%	4	30	1.81	0.49	$ 610
7-A	33.8	-32%	224%	2	35	2.60	0.49	$ 612
4-A	34.7	-53%	(-23)%	2	38	2.19	0.46	$ 648
15	24.4	-54%	99%	7	25	1.77	0.46	$ 650
9-A	47.1	-47%	136%	18	45	1.09	0.45	$ 670
14-B	55.3	-54%	24%	12	40	0.67	0.44	$ 676
7-B	43.1	-32%	66%	4	35	0.49	0.37	$ 816
16-A	37.5	-72%	(-14)%	20	50	0.24	0.21	$ 1,396

Regression analysis (Table 3) as expected shows the greatest influence on delay free mastication time is acres treated. Large units generally take longer to masticate than small units (Table 3). Regression further showed significance associating slopes with angles above 35% tending to impact mastication efficiency the greatest. Our observations agree as the unit with the steepest slope also had the highest treatment cost. In contrast to our field observations we did not find a significant relationship among the density of residual trees and machine production. Most likely slope angle, fuel structure, fuel juxtaposition, administrator intervention, and the interaction of all factors singly or in combination played a greater role in machine efficiency than residual tree density alone.

Table 3. Regression model predicting average mastication time (in centi-minutes)

Coefficients	Range for independent variables (mean value)	n	R^2**	P-value
23.62		19	0.87	
+80.53*(Acres)	0.24 - 4.46 acres (1.88)			0.000
+32.89*(Slope catagory)	1 if 35% slope or greater (0 if not)			0.084

** Adjusted R^2 (Includes a penalty for increasing the number of independent variables)

An integral part of using machinery in completing a task is that a variety of factors can prevent the machine from operating as planned. Over the 65.34 hours the machine worked, 2.55 hours (4% of the total time) were attributed to activities other than mastication (Table 4). Mechanical delays include several instances where the operator had to clear debris from the radiator and cool the hydraulics. Another significant mechanical delay occurred when a dead tree fell onto the boom cracking a hydraulic hose connection. Mechanical delays were minimal during our study due to a combination of significant mechanical preventative maintenance during the off-season and a relatively new machine. Due to the research aspect of this project, the administrator observing and directing the fuel treatments gave instructions or answered questions from the operator by 2-way radio. Because the operator idled the machine during these events, they were considered an administrative delay. Delays of this type are normally lower on non-research related projects. Various operational delays such as transitioning from roadside to the unit and planning the work method occurred throughout the project.

Table 4. Proportion of machine time not treating fuels (based 65.34 hours observed).

Delay Category	Occurrence (%)	Example
Operational	38	Accessing unit, Clearing debris, Planning
Administrative	22	Receiving instructions from forester
Mechanical	35	Broken hydraulic hose, Cooling hydraulics
Personal	6	Operator rest periods

3.2 Fireline Construction

Four firelines were constructed using the excavator with the rotary head. A total of 2326 feet of line was constructed divided into 11 sections based on slope, fuels, and/or terrain. Two operators built fireline with the masticator however neither operator had experience building line previously. The fuel break they created averaged 17.8-feet wide and included the removal of aerial fuels or trees and branches extending out over the fuel break. A 4-foot wide fireline cleared to mineral soil was constructed down the center of each segment. Pre-fuel break total debris estimates (including activity fuels) ranged from 26 to 61 tons per acre (Table 5). Under these conditions 7.3 feet per minute (or 440 feet/hour) of fuel break and fireline was constructed costing approximately $72 per 100 feet using a moderately experienced operator.

Table 5. Characteristics, production, and costs associated with fireline construction using a mastication machine in mixed conifer forests.

Segment	Estimated tons/acre	Slope (%)	# of pieces by diameter size crossing fireline 3-6"	6"+	Production (ft/min)	Cost ($/100 ft)	Constraint
4-1	49	38	11	12	6.0	$ 83	None
4-2	42	25	14	13	7.7	$ 65	None
4-3	61	30	16	26	9.4	$ 53	None
6E-1	61	30	8	10	5.1	$ 98	None
6E-2	49	15	13	19	9.3	$ 54	None
6E-3	26	28	26	24	8.6	$ 58	None
6W-1	45	25	17	27	4.5	$ 111	Activity fuels
6W-2	45	10	39	60	8.7	$ 57	Remove large pieces
6W-3	45	28	10	26	6.2	$ 81	Combination
7W-1*	43	45	46	37	9.6	$ 52	(See note)
7W-2*	43	24	20	14	18.3	$ 27	(See note)

* Experienced operator: Simulated limited maneuvering, and required to build 3 waterbars on 1st segment

Fireline construction necessitates that the area of the line be free of burnable materials. In the instance of using a horizontal revolving head it had the tendency to throw branches, limbs or other slash out of the proposed burn area or across previously built fireline. These situations not only required additional fireline construction time, but in many circumstances it increased the amount of fine fuels adjacent to the protected side of fireline elevating the risk of these fuels igniting during the prescribed fire. As such the construction of firelines using a horizontal masticator needs to ensure that the material thrown by the machine does not land on the cleared fireline or in areas that would increase the risk of unwanted fire. For the most part this can be controlled by the direction the machine travels when building fireline.

In general fuel treatments using a masticator have different objectives and desired conditions compared to fuel breaks and firelines. As such building fire breaks through large amounts of fuel using a masticator may require additional resources. Considerable time is often required grinding and/or chopping large fuels into small pieces. Less time is required if these large fuels are moved outside the fuelbreak using the machine's "thumb". Though not used during our study, the addition of a ground's person following a safe distance behind the machine could reduce construction time by removing loose debris from the fireline.

A combination of operator experience and different work methods increased production of fuel breaks and firelines significantly (Table 5). For example, we used a highly experienced operator to build fireline on a steep slope. We further constrained the operator by limiting his ability to rotate the machine (simulating tight working conditions), and required three water diversion ditches be installed on the steep slope. Even with these challenges the operator was able to build a fuel break and subsequent fireline for as low as $27 per 100 feet (Table 5).

Masticators appear to be an option for building firelines through large accumulations of downed material. Moreover, our data suggest that the lines can be low impact even though they averaged 17.8 feet in width due to limited soil disturbance except for the fireline. Most often root systems and grasses remained after fuel break construction reducing erosion potential. Site impacts and rehabilitation costs can be low using a masticator, however production may be less compared to dozers.

3.3 Additional Research Needs

There are a variety of masticating machines manufactured by numerous firms. Ideally their costs and effectiveness could be disclosed to fully evaluate their potential for treating fuels and preparing sites for planting in western forests. Moreover, the operating efficiencies of different mastication heads (e.g., horizontal or rotary) would also be useful information in conjunction with site factors, (e.g., slope, soils) and size, amount, juxtaposition, and composition of fuels (vegetation) being treated. This study used a large excavator based machine equipped with an auxiliary hydraulic system (80 gpm) for the mastication head. Most other machines which include feller-bunchers (80 gpm) and other excavators (40 gpm) use the same hydraulic system to power the tracks, swing the boom, and power the mastication head. As a result, our production may be higher than some masticators and research as such could address this unknown. Also smaller machines in general have lower operating costs that offset decreased production. Information addressing these issues is needed.

4. CONCLUSIONS

Fuels were treated on 37.07 acres in a moist, mixed conifer forest in northern Idaho using a large excavator based machine with a rotary head equipped with a thumb. To encourage decomposition, the fuels were chunked rather than chipped. A critical component of using masticators or for that matter any machine that rearranges or alters fuel structure is to ensure that the resulting fuel condition does not exacerbate fire risk, immobilize nutrients, insolate the soils, or retard decomposition. Fine fuels, < 3 inches in diameter are usually considered the hazard in most forests and their disposition is critical to determining fire risk. Therefore, masticators should chunk fuels keeping as many pieces as possible greater than 3 inches and placing them in contact with the soil surface, to encourage decomposition. Fine fuels will invariably be produced using masticators but those too should be dispersed as not to create concentrations. By far the operator has the greatest control of the size of material remaining after treatment. Because of human nature to make things look tidy and neat operators tend to grind material more than necessary to reduce the fire hazard and doing so they use more machine time which increases costs and can produce less than desirable soil and fuel conditions. Immediately after treatment fire risk most likely increases but by leaving a heterogeneous fuel loads, decomposition will most likely be accelerated and the hazard will subsequently decrease. A key to achieving the desired conditions is a competent operator and constant communication between the operator and an on-the-ground observer/administrator so the masticator creates the desired fuel conditions

In our study slash created by timber harvesting and unwanted standing trees were chunked at an average rate of 0.57 acres/hour. The slopes, fuel conditions, and residual tree densities in this moist forest were highly variable resulting in the fuel treatments averaging $530 an acre. More than any other factor slope angle tended to decrease production especially when the machine worked on slopes over 35%. Although not significant, as residual tree density increased costs tended to increase due to additional machine moving required and inability to freely swing the boom to prevent damaging residual trees. However, in addition to slope angle and tree density singly or in combination, fuel structure, fuel and tree juxtaposition, operator experience, and the desire to produce neat and tidy conditions also impacts production.

The costs we observed in this study on their face value appear to be relatively high; but the fuel and site preparation treatments occurred irrespective of the weather, no follow up activities (e.g., burning piles) were required, fire intolerant trees were protected, large and high value western white pine trees were protected, and sites have been prepared for both natural regeneration and planted trees. Prescribed fire and piling of slash are frequently used in these forests to treat fuels and prepare regeneration sites. However, both require multiple entries for the task to be completed. Often hand crews need to cut small or unwanted trees prior to either a grapple machine piling the fuels or burning them with prescribed fire. To save fire intolerant residual trees necessitates that fuels be pulled away from them and special ignition and/or protection (e.g., foam) may be needed prior to using fire. The use of fire brings issues such as impeding air quality, fire escaping, or causing residual tree mortality. Furthermore, if sites are not ready for planting trees when planned high value seedlings could be lost, potential forest growth could be lost, and the window of using prescribed fire because of shrub and grass vegetation development cold be lost. Within this context mastication costs may not be that prohibitive.

The large masticator we used built fire breaks incorporating a center fireline at an average rate of 7.3 feet per minute (440 feet/hour). Again these breaks were through moist forest slash created by timber harvesting including aerial fuels. In concentrations of large logs the masticator needed to remove these large materials using its thumb which improved fireline production. Even though fireline construction with a masticator is possible in these conditions it appeared to be far from optimum. We built fireline in various situations with the machine and with a moderately experienced operator it cost an average of $72 per 100 feet of fireline built. These costs can be greater than those built with crawler tractors but increased production and lower costs may be possible if an experienced operator was used. From a soil conservation view, masticator built firleine may require less rehabilitation due to limited soil disturbance and lack of windrowed soil/fuel combinations adjacent to fire lines which is a common occurrence with tractor built lines.

Fuel and site preparation treatments are fundamental to managing forests throughout the western United States. Because of their flexibility as to their timing, intensity, and machine types mechanical treatments are often preferred. This study illustrates how masticators can be used to fill this need demonstrated in the moist forests of northern Idaho.

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Chloride Stabilization of Unpaved Road Aggregate Surfacing*

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Abstract
There are few alternatives for improving performance of aggregate surfacing materials other than annual dust abatement treatments. In place stabilization of properly graded aggregate with chloride additives is cost effective and provides many performance and intangible benefits in many environments. This two year study identifies conditions where chloride stabilized roads have a projected life of 10 years or more if properly maintained. The greatest benefits are realized on projects where aggregate surfacing replacement costs are high and average daily traffic volumes exceed 100. Stabilization provides a much higher standard of road surface performance by improving ride quality, and reducing dust, corrugations (washboarding), and raveling (loose aggregate). Other intangible benefits include reduced sedimentation in streams, reduced aggregate resource depletion, reduced health hazards from dust, and increased road-user safety. Similar results are achieved by plant mixing additives with aggregate during crushing. This project developed guidelines for chloride stabilization of different aggregate surfacing materials in semi-arid to arid environments. Performance and cost effectiveness of chloride stabilization was measured on 12 projects and monitored for 2 seasons in 4 western States. Project monitoring included the following; construction and maintenance costs, road surface deterioration, traffic, weather conditions, environmental effects, and materials testing. Results show that treated surfacing needed blading maintenance after 25,500 vehicles, where untreated surfacing needed blading after only 3,200 vehicles; thus treated road performance life was 8 times greater than untreated. Environmental affects on trees, streams and roadside soils were insignificant.

1. INTRODUCTION

Each year, most low volume road agencies maintain thousands of miles of unpaved aggregate surfaced roads by surface blading. Blading is a costly activity that is done frequently and lasts a short time on heavily traveled roads. Road surface conditions can deteriorate so fast that blading is often recognized as an ineffective but politically necessary activity. Blading also contributes to the increase of stream sediments and contamination, loss and breakdown of expensive aggregate surfacing.

When utilized correctly, road surface stabilization with magnesium and calcium chloride materials reduces blading significantly, increases road quality and saves money. These two chlorides absorb moisture from the air and retain this moisture because they are both

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 149-156.*

deliquescent and hygroscopic. They promote greater density and capillary tension of fines in aggregate surfacing that helps bond the materials together. Application rates used for stabilization are three to five time the normal application rate used for dust abatement.

The goal in road selection was to get a broad cross section of roads—that were in relatively dry climates—in three USDA Forest Service Western Regions. Twelve roads were selected in four states. Each road had three types of test sections. Some were maintained according to usual practices, others were mixed with chloride materials, and some were untreated control sections.

Test sections were constructed with liquid and solid forms of calcium chloride and liquid magnesium chloride, and then performance was monitored for two years. Thirty-nine treated and 40 untreated test sections were built with magnesium and calcium chloride mixed at 2 concentrations with crushed aggregate surfacing 2 inches deep. Chlorides were mixed to provide 1.5 and 2.0 percent pure chloride salt based on dry weight of aggregate. They were mixed in place with a motor grader and also with an agriculture type tractor tiller.

Performance monitoring, measurements, and testing were a significant part of this project. Road surface defects were measured three to four times each season to develop deterioration curves and to determine the effective life of each type of treatment. Deterioration curves' using a condition index was the basis for performance measurement and life prediction. The primary inputs for a life cycle cost analysis were treatment life and costs for aggregate loss, construction, maintenance, and for the road user. Environmental affects were measured before and after construction by testing chloride concentration in roadside soils, trees and adjacent streams. Continuous onsite traffic and weather monitoring was conducted on all projects for the two year period. Extensive testing was done to define aggregate characteristics on all projects.

2. PROJECT SCOPE AND OBJECTIVES

From 1995 to 2000 the USDA Forest Service completed three projects using in-place stabilization with solid calcium chloride that showed promise in extending aggregate surfacing life and performance, as well as reducing maintenance (Monlux 2003). This project replicates these practices on a larger scale by including other types and forms of magnesium and calcium chloride, additional construction practices, different aggregates and climates. Monitoring efforts were intensified for road surfacing performance, weather, traffic, and effects on soil, stream water and trees. More detailed analysis was done on costs and benefits. The primary objective was to provide guidelines and tools for effective implementation of the technology.

3. TEST SECTION DESIGN

Within each road, test area location was based on similar aggregate, exposure, canopy, aspect, grade, and curvature. Three types of test sections were constructed on each project. At least one untreated control section was mixed with the blade or tractor-tiller to see if the construction process provided significant benefits by itself. At least one section was built to model the normal maintenance blading. All other sections were treated with chloride materials in various forms and application rates. Test section lengths ranged from 750 to 900 feet. Seventy-nine test sections were constructed.

4 TEST ROAD CONSTRUCTION

A service contract for construction was awarded to Moline Grading, Standpoint, Idaho, in September 2002. Oxford Inc., Moyie Springs, Idaho, provided, applied, and mixed all chloride materials. The Trout Creek Road project was built as a pilot project in October 2002. The remaining 11 projects were built between mid May and early July 2003. The general construction process was as follows:

- All sections were watered to assist the initial blading and shaping.
- All sections were bladed to remove ruts, washboards, potholes, and mix in loose aggregate. The road surface was shaped to a 4-percent crown.
- Where solid (dry) products were used, the road surface was watered to ensure that the aggregate would be at optimum moisture during mixing. Water was not applied to the road surface prior to mixing liquid products for fear of exceeding optimum moisture.
- For tractor-tiller mixed sections, chloride was applied and tilled into the top 2 inches of aggregate. The surface was lightly shaped to ensure a 4-percent crown and then compacted. A light surface application of chloride was spread on the finished surface.
- For blade-mixed sections, a windrow was built, sized, and flattened. The size of the windrow is based on a 2-inch compacted depth times a 1.25 swell factor. Chloride materials were spread on the flattened windrow then mixed by moving material from one side of the road to the other, two times. The mixed surfacing was spread from the windrow, then shaped to a 4-percent crown and compacted. A light surface application of chloride was spread on the finished surface.
- Twenty-two untreated control sections were built using the same methods as treated sections, except chloride materials were not used.

5. PROJECT MONITORING

5.1 Weather

Relative humidity and temperature were measured by onsite gauges on all 12 projects. Rainfall was measured onsite on six projects, and remote automated weather station data was used on the other six projects during 2003. In 2004, all projects had onsite rainfall gauges.

Average daily relative humidity ranged from 15 to 98 percent and temperature ranged from 35 to 98 degrees Fahrenheit. Average seasonal relative humidity and temperature ranged from 47 to 83 percent and from 50 to 61 degrees Fahrenheit. Precipitation during the spring, summer, and early fall was light in 2003 (0.5 to 5.5 inches) and heavy in 2004 (5.3 to 13.9 inches). About two-thirds of this precipitation occurred during the hot summer months as isolated thunderstorms dropped 0.3 to 0.5 inches of rain over a 1-hour period.

5.2 Traffic

Vehicle traffic counts were collected on all 12 projects. The South Side Road had the lowest seasonal average daily traffic (25), and the Middle Fork Payette River Road had the highest (157). Four of the 12 roads had peak daily traffic counts of over 400 vehicles with the greatest count being 922. The primary operating season is from April to November and is controlled by freezing road conditions or snowfall.

Traffic classification was provided by forest road managers and generally fit into the three categories:

- 79 percent light vehicles including trucks.
- 16 percent 2-axle trucks and light-duty trucks with trailers.
- 5 percent trucks with more than 2 axles.

5.3 Soil, Water, and Tree

Environmental influences were measured by testing chloride concentration in roadside soils, trees and adjacent streams before and after construction. Forty-eight samples of soil, from both treated and untreated sections on the road shoulder were taken before construction on each project. After 2 seasons, 48 additional samples were taken on these same locations to see if there was a significant change in chloride concentration. The data shows a rise in soil chloride levels that are below the thresholds for concern.

Chloride levels in the Tucannon River were measured before and after treatment of the Tucannon River Road. The river varied 15 to 20 feet from the road shoulder. Results indicate there is no significant change in calcium or chloride-ion levels in the water after treatment.

On 4 projects, before construction, 101 samples of conifers were taken close to the road and adjacent to a treated and an untreated test section. Locations of trees ranged from 5 to 50 feet from the road shoulder. Duplicate samples were taken from the same trees after two growing seasons to see if there was a significant increase in chloride concentration. Data from tree samples indicates the level of chloride increased, but is not a significant long-term threat to survival.

5.4 Road Surface Performance

Road surface defects were measured three to four times each season to develop performance curves and determine the effective life of each test section. All monitoring was done by one individual to improve consistency.

The un-surfaced road condition index, URCI, was used to monitor road surface performance *(USACE 1995)*. The URCI is a road management tool for scheduling maintenance and avoiding costly repairs. Similar but less measurement-intensive methods are used by many low-volume road agencies. The distress types or defects rated for these projects are corrugations (washboards), dust, potholes, ruts, and loose aggregate (raveling).

Each distress type measured is categorized into three severity levels (low, medium, and high) and the extent of each level is measured in square feet. Each measured distress level is converted into a value and subtracted from 100 to get the condition index. A road with no defects has a condition index of 100. Values below 60 usually indicate that blading is needed.

Road surface conditions were observed to determine if blading was needed and to determine reasonable vehicle speed on each section. Vehicle speed influences user costs and provides another indication of road serviceability. Reasonable vehicle speeds and corresponding thresholds for "blading needed" and "blading critical" are on performance curves to provide a better description of the extent of deterioration that was taking place during each season. A 25 percent reduction in vehicle speed correlates with "blading needed" and a 40 percent reduction in vehicle speed correlates with "blading critical".

One method for describing performance is by using the life ratios. Life ratio is defined as the amount of traffic on treated sections divided by the amount of traffic on untreated sections prior to blading being needed. Essentially, the ratio is a number that represents how much longer the initial performance life of the treated sections is versus the untreated sections prior to maintenance blading. The ratios range from a low of 4 to a high of 57. Based on the average life ratios of all projects, treated sections needed blading after 25,500 vehicles and untreated needed blading after 3,200 vehicles; thus the average life ratio for all projects was 8.

6. LABORATORY TESTING OF AGGREGATE AND CHLORIDE MATERIALS

Road-surfacing aggregate on 11 of the 12 projects is good quality, well-graded crushed aggregate. Gradation tests show from 48 to 72 percent passing the #4 sieve, and 11.1 to 17.2 percent passing the #200 sieve. These types of gradations have been found to perform well in relatively dry climates because they capture the chloride ions in a relatively impervious gradation *(Slesser 1943).* Impervious gradations prevent rains from flushing chloride ions in the aggregate down into the subgrade. Less amount of minus #200 would be necessary if the minus #40 were plastic. Aggregates on all projects are nonplastic, including the Payette River Road aggregate that was treated with 2.5 percent bentonite clay in 1999.

The percentage of chloride used for stabilization was based on past experience on several stabilization projects. The 1.5 and 2 percent chloride salt concentrations by weight aggregate surfacing are similar to concentrations obtained by annual dust abatement treatments over a 4- to 6-year period. An indication of the optimum chloride content for a particular aggregate can be determined by running moisture density tests with various percentages of chloride, similar to an asphalt mix design. Higher rates last longer in arid areas because higher concentrations evaporate at a slower rate *(Slesser 1943).*

7. INTANGIBLE BENEFITS

Stream sediments are reduced when road surface blading is reduced *(Foltz and Truebe 1995).* This project shows that blading is reduced when road surfaces are stabilized. When stream sediments are reduced, costs are reduced or eliminated for design, construction, and maintenance of sediment control structures.

Resource damages from aggregate sources are reduced if the demand for aggregate surfacing is reduced. Road surface stabilization clearly reduces the need for aggregate replacement. Less aggregate usage would conserve aggregate resources which are scarce in many areas, and save funds currently spent for locating, drilling and surveying new sources, preparing pit development plans, securing necessary permits, and for site development and restoration.

Road user safety is increased when dust from the road surface is reduced. Chloride materials are an effective dust abatement product, as well as a stabilization agent. Less dust reduces vehicle accidents, which reduce costs associated with vehicle repair and medical expenses, as well as decreasing loss of life.

Public health costs are less when a known health hazard, such as dust, is reduced. The extent of the benefit is based on the amount type and speed of vehicular traffic, the number of vehicle occupants, and the number of individuals exposed for long periods in roadside residences and campgrounds.

Negative public opinion is generated from roads in poor condition. Public complaints require valuable employee resources that adversely affect the road agency workforce's overall productivity.

8. OBSERVATIONS AND CONCLUSIONS

The following conclusions are from field observations and data collected during full scale monitoring during the 2003 and 2004 seasons, and limited monitoring after blading maintenance in 2005.

8.1 Treated Sections versus Untreated Sections

- Blading was needed on treated sections after 25,500 vehicles, and on untreated sections after 3,200 vehicles, thus the average initial performance period for the treated sections lasted 8 times longer than the untreated sections.
- The average speed on treated sections was 37 miles per hour and the average speed on untreated sections was 26 miles per hour for the 2-year period.
- During the 2003 season, four of the 39 treated sections needed blading one time and all 40 untreated sections needed blading 95 percent of the time. Blading became critical on several untreated sections in the first year.
- Visual observations indicate treated sections reduced the dust by approximately 90 percent, thus reducing inhalation health hazard.
- The condition of all test sections improved after periods of wet weather and over the winter season. Treated sections improved more than untreated sections.

8.2 Treated Sections

- During the first 2 years of monitoring, 13 of 39 treated sections needed blading. Six of the 13 sections had construction problems or the crown was removed by snowplowing. The predominant defects in the other seven sections were potholing, washboarding, and rutting.
- All the pothole problems existed where the crown was less than 2 percent due to snowplowing or at the centerline where the crown was flattened. Water in potholes may leach chloride from the treated surface into the subgrade.
- No distinct difference in performance existed between the 4 different products, magnesium chloride liquid, calcium chloride liquid, and calcium chloride solid at 77- and 94-percent salt concentration.
- No distinct difference existed in performance was noticed on 2 percent chloride content versus 1.5 percent. A greater difference in performance may be evident after 3 or more years of service.

- Aggregate materials on 11 of 12 projects performed well when stabilized. Miller Creek Road was the exception because there was more loose aggregate material that caused raveling. All other projects were essentially 3/4-inch minus and well graded with a minus #200 range of 11.2 to 17.1 percent and no plasticity. Well-graded aggregates with this amount of minus #200 work well because chloride ions are held within a relatively impervious medium (4). Minus #200 contents between 8 and 12 percent may also work well if minus #40 portion was plastic.
- No correlation existed between project performance and gradations plotted on the 0.45 power curve.
- In dryer climates, treated road surfaces may dust in early spring before spring rains. These surfaces regain their treated appearance (wet look), and harden-up when rains come or when the surface is watered.
- All project characteristics influence the performance of chloride-treated aggregate surfaces. The most significant appear to be aggregate characteristics, climate, maintenance blading practices, traffic speed and volume.
- Humidity influences performance. However, projects with an average daily minimum humidity as low as 15% in Central Oregon performed as well as some projects with higher humidity. Periodic rains improve performance, but do not have as significant an influence as daily humidity. Projects located next to streams or that had roadside vegetation to provide shade, performed better.
- Blading when moisture is below optimum or allowing the bladed surface to remain loose and dry out reduces long-term performance. The wet blading process works very well for relatively impervious gradations. The road surface is saturated after blading, and then wheel tracked to flush fines and residual chloride to the surface. When the surface dries, a hard crust develops that can last as long as the original treatment.
- Pothole formation or resistance to surface erosion is not improved by chloride stabilization. Road crown is the primary deterrent to the formation of potholes and surface erosion.

8.3 Construction

- Superior performance of treated sections over untreated control sections indicates that the good performance is due to stabilization agents and not the stabilization construction process.
- There is no significant difference in the performance of untreated normally bladed sections and untreated compacted control sections. This indicates compaction after maintenance blading has no long-term performance benefits.
- "Normal blading" practices used for removing all road surface defects were as effective as milling or blade-mixing 2 inches deep. However, the "normal blading" costs $284 per mile on test sections and removed many more defects and built better crowns than the typical maintenance blading. Typical maintenance blading costs on 8 of the 12 roads are $157 per mile. During the second season contract-bladed untreated sections developed defects more rapidly.
- The best time to stabilize aggregate roads with chloride is early spring when road surface moisture content and humidity are high and late spring rains keep the surface wet while traffic flushes fines to the surface. The fines form a hard crust when dry.
- Blade-mixing consistency is very dependent on operator capability and machine condition.

- Blade-mixed sections deteriorated more rapidly than tractor-tiller mixed sections, due to treatment depth inconsistencies and non-uniform mixing. Minimum depths of 2.5 inches are needed when blade mixing.
- Blade mixing liquid chlorides is not practical on roads with grades over 2 percent, because the product will run in distributor wheel tracks to sag vertical curves or off the road surface.
- Blade-mixing operations require more quality assurance and technical expertise to ensure the correct amount of aggregate is mixed with chloride and that the treated thickness is uniformly mixed to the specified depth.
- Blade mixing is not practical where road widths are less than 18 feet.
- Traffic delays and construction interruptions with blade mixing are more significant than with tractor-tiller mixing for all chloride products.

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Evaluating Forest Road Construction Techniques: A Case Study of the Right-of-Way Logging and Construction Activities*

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Abstract
The forest road construction process is comprised of many phases including trailing/falling, skidding, processing, loading and hauling, and road and landing construction. Currently, there is little information available on the productivity and costs of alternatives for these phases. FERIC has initiated a series of case studies to document and evaluate the construction techniques, and investigate interactions between road construction and right-of-way logging activities. Field work for the first study was completed in southeastern British Columbia in January 2006 and data analysis is in progress. This paper introduces the study series and provides a brief description of the study methods being used. An overview of the construction technique used in the first case study is presented.

1. INTRODUCTION

In British Columbia's Interior region, the conventional road building process is comprised of several phases including pilot trail construction, right-of-way felling, right-of-way skidding, log processing, log loading and hauling, and road and landing construction. There are many variations of the road building process but typically the roads are built in stages, with the equipment used for each phase continually switching positions along the right-of-way. Conflicts between road construction and right-of-way logging activities cause inefficiencies and poor equipment utilization.

As a result, many forest companies in the Interior would like to investigate alternative construction strategies. Currently, there is minimal information available on the productivity and costs of alternatives, so FERIC initiated a series of case studies to evaluate construction techniques. The studies will provide needed data on road building operations to help managers make decisions about where and when to apply alternative techniques, and to improve their assessments of operating costs.

Field work for the first study was completed in southeastern British Columbia in January 2006 and data analysis is in progress. This paper introduces the study series and provides a brief description of the study methods being used. An overview of the construction technique used in the first case study is presented.

2. OBJECTIVES

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 157-163.*

The objectives of the studies are to:

- Document selected road building techniques.
- Evaluate equipment utilization levels, productivities and costs by phase.
- Determine how the road building phases interact, identify inefficiencies between the right-of-way logging and subgrade construction activities, and recommend improvements.

3. STUDY METHODS

A case study approach is being used to evaluate road construction productivity and costs for selected construction techniques. FERIC is conducting two types of production studies, known as shift-level and detailed-timing studies. The two methods are complementary and are carried out concurrently. The combined approach provides the data needed to determine equipment productivities and costs, to analyze the interaction between construction phases, and to characterize the construction technique.

3.1 Shift-level study methods

All machines used for right-of-way logging and road construction will be equipped with MultiDAT electronic dataloggers. MultiDAT units will be connected to a machine's power supply to continuously monitor machine function. They will have four channels for electronic inputs, a channel to record machine vibration, and Global Positioning System tracking capability. The MultiDATs will be installed in the machine cabs accessible to the operators. For these studies, the dataloggers will be programmed to accept operator inputs identifying machine activity and sources of delays. The MultiDAT units will accumulate shift-level information about productive time, and mechanical and non-mechanical delays for each piece of equipment. The MultiDat units will have GPS capabilities and, thus, will be set to collect positional information for each machine at specified time intervals. The machine type and job function dictate the collection interval. More mobile machines (e.g. skidders) will have a more frequent point collection rate than more stationary equipment (e.g. excavator). The data collected from the machines will illustrate the position of a piece of equipment in time throughout the project study area. By having this positional, productivity and cost information, the cost of any selected area (zone) within the study site can be investigated.

The information from the dataloggers will be supplemented with daily shift reports. Two machine operators, one from the right-of-way logging crew and one from the construction crew, will complete the forms. The shift reports are used to gather additional information about equipment function and the road building process that would not be recorded by the MultiDATs alone. For example, descriptions of equipment downtime or unforeseen conditions encountered during construction will be noted on the forms.

FERIC researchers will visit the site regularly to download data from the MultiDATs, collect shift reports, observe the construction process, and discuss the operation with the crews. Digital photographs and video will also be taken during these site visits to further document the road building system.

3.2 Detailed-timing study methods

For some machines, productive time will be made up of several activities. For example, an excavator may push-fall right-of-way timber, construct a pilot trail, rearrange and present felled timber for skidding, and construct the final road prism. Major divisions in productive time will be captured in the shift-level data. However, to distinguish between the finer points of some phases, such as whether an excavator is push-falling timber or presenting it for skidding, detailed-timing methods must be used.

For each machine, the specific time elements that make up productive time will be identified in the field by the lead FERIC researcher. Detailed-timing of productive activity will be carried out by researchers who will use a stopwatch or a handheld computer programmed for equipment monitoring. Descriptive statistics for the elements of productive time will be developed and summarized in the final project report.

3.3 Equipment time distribution, productivity and costs

Total scheduled time, known as scheduled machine hours (SMH), will be summarized for each piece of equipment used in the project. Scheduled machine hours are the sum of productive machine hours (PMH), non-mechanical delays (NMD), and mechanical delays (MD).

Road construction production will be measured as lineal metres of completed road. For the right-of-way logging phases, the volume (m3) of timber processed will also be measured. Phase productivities will be calculated by dividing the measures of production by the time spent on right-of-way logging and subgrade construction.

Hourly equipment rates, comprised of ownership and operating costs, will be developed by FERIC for each machine. The rates will be generic rates applicable to the makes of machines used in the study as well as to other makes of the same type and weight class. Shift-level time and production information will be applied to the hourly equipment rates to determine the unit costs for the project. Unit costs, in terms of $/lineal-metre of road, will be presented for all phases of the project. Unit costs, in terms of $/m3 of right-of-way timber, will also be presented for the right-of-way logging phases.

4. THE "RAVENSHEAD" CASE STUDY

The first in the series of road construction studies was the Ravenshead project, located approximately 50 km east of Radium Hot Springs, B.C. The roads for the Ravenshead project were constructed in 30 working days falling within the period from November 18, 2005 to January 11, 2006. During this period, six machines were equipped with MultiDAT data recorders. The crew also recorded its activities on daily shift reports.

4.1 Site description

Located in the Interior of British Columbia, the study site is within the Kootenay Range of the Rocky Mountains on the eastern slopes of the Kootenay River Valley (Figure 1). The site is on public land outside Kootenay National Park. The logging and construction activities of this project were completed by one multi-phase contractor working for a major forest company.

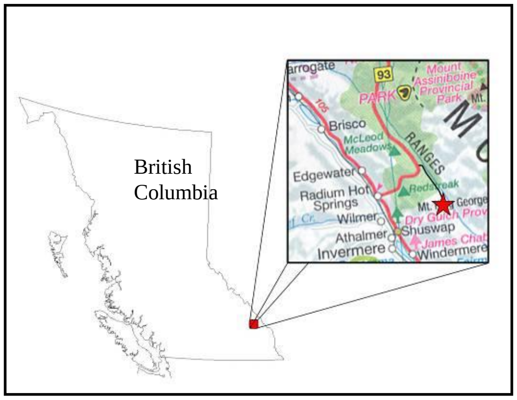

Figure 1. Study site location.

The roads associated with this study consisted of 4.6 km of new construction, and developed 98 ha of harvestable timber (see Figure 2). The cutting units were comprised of lodgepole pine (Pinus Contorta Dougl.), Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco) and white spruce (Picea glauca (Moench) Voss) with an average age of 80 years. The stands were in the early stages of mountain pine beetle (Dendrotconus ponderosae Hopkins) infestation. Terrain conditions were flat to undulating with slopes ranging from 0 to 60 percent. The soils were silty clays overtopping limestone bedrock. Several small sections of highly fractured limestone rock were scattered throughout the project site, but rock was usually avoided and ripped only when necessary.

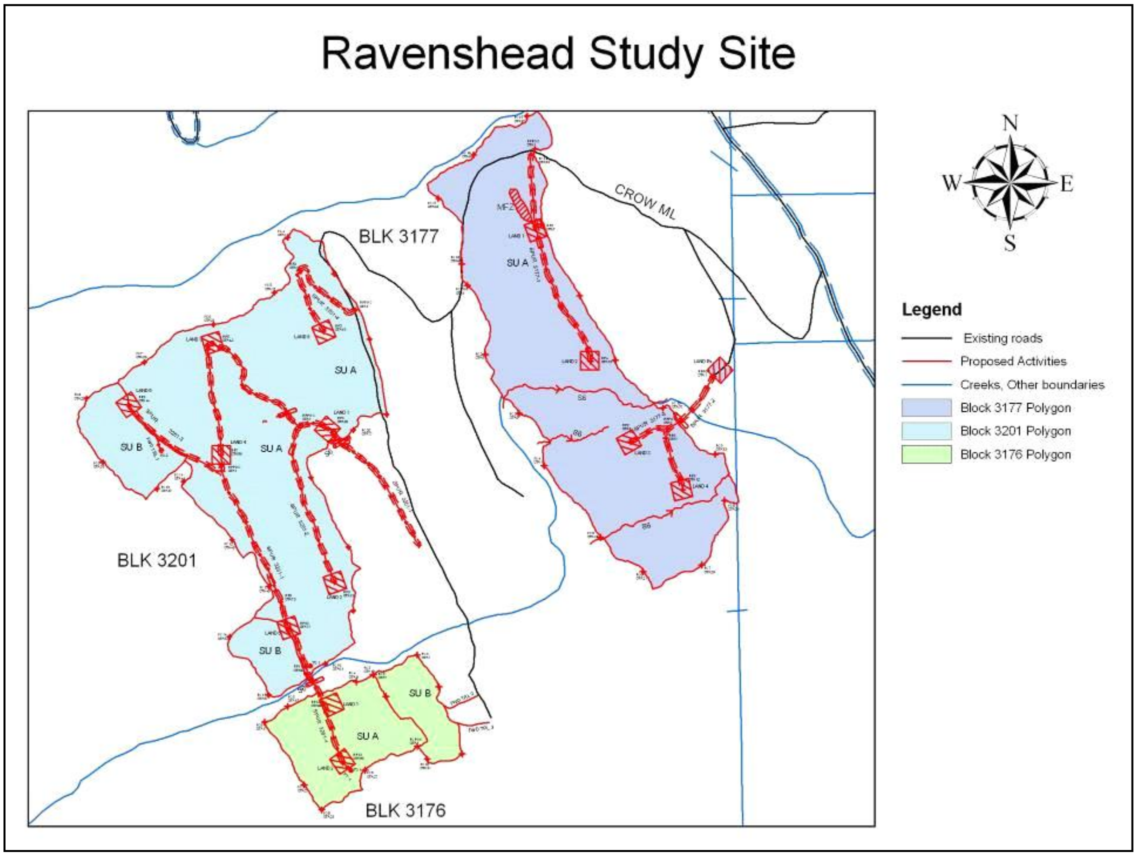

Figure 2. Study site road network.

4.2 Road construction technique description

The right-of-way logging and road construction activities were closely coordinated on the Ravenshead project to produce a finished road in a systematic manner. A description of the main phases and the corresponding crew tasks follows. The overall process is illustrated in Figure 3.

4.2.1 Logging activities

Trailing/falling phase. A Caterpillar 320C LU excavator initiated pilot trail construction. The machine push-felled the trees in its path and concurrently constructed a narrow, 3-m-wide, stump-free skid trail within the lower half of the clearing width. This machine worked closely with a hand faller, and in some cases the operator had dual responsibilities as operator and faller. The faller’s job was to manually fell the upper half or remaining portion of the clearing width and landing areas.

Skidding phase. The skidding phase was completed using one, and sometimes two, Caterpillar 518 cable skidders. Tree-length stems were skidded along the newly constructed trail to the nearest finished landing. The stems were subsequently processed on the landing.

Processing phase. The processing phase was completed manually with a Caterpillar 315 excavator used to handle the stems and pile debris generated during this phase. The operator manually bucked and delimbed stems, and carried out any other activity necessary to convert the stems to their required specifications.

Loading and hauling phase. The logs were loaded using a Western Star self-loading tridem drive with tridem pole-trailer logging truck. This phase was carried out concurrently with road construction activities.

4.2.2 Construction activities

Road and landing construction phases. The construction activity is characterized by two phases—road and landing construction. These phases were completed with a John Deere 3554 excavator in conjunction with a Caterpillar D7R XR bulldozer.

In both the road and landing construction phases, the excavator pioneered ahead near the road centerline, but above the previously constructed pilot trail. Stumps and debris were placed on the outer edge of the subgrade fill. While moving forward, the excavator placed a windrow of material for the bulldozer to spread along the road centerline. The bulldozer shaped the material and established the finished grade level.

Table 1 lists the type of equipment used on the project by phase.

Table 1. Equipment used on the project by phase

Phase	**Equipment used**
Trailing/falling	Caterpillar 320C LU (22 000 kg) excavator
Skidding	Caterpillar 518 cable skidders
Processing	Caterpillar 315 (16 000 kg) excavator
Loading and hauling	Western Star self-loading tridem drive with tridem pole trailer
Road and landing construction	John Deere 3554 (39 000 kg) excavator Caterpillar D7R XR (26 000 kg) bulldozer

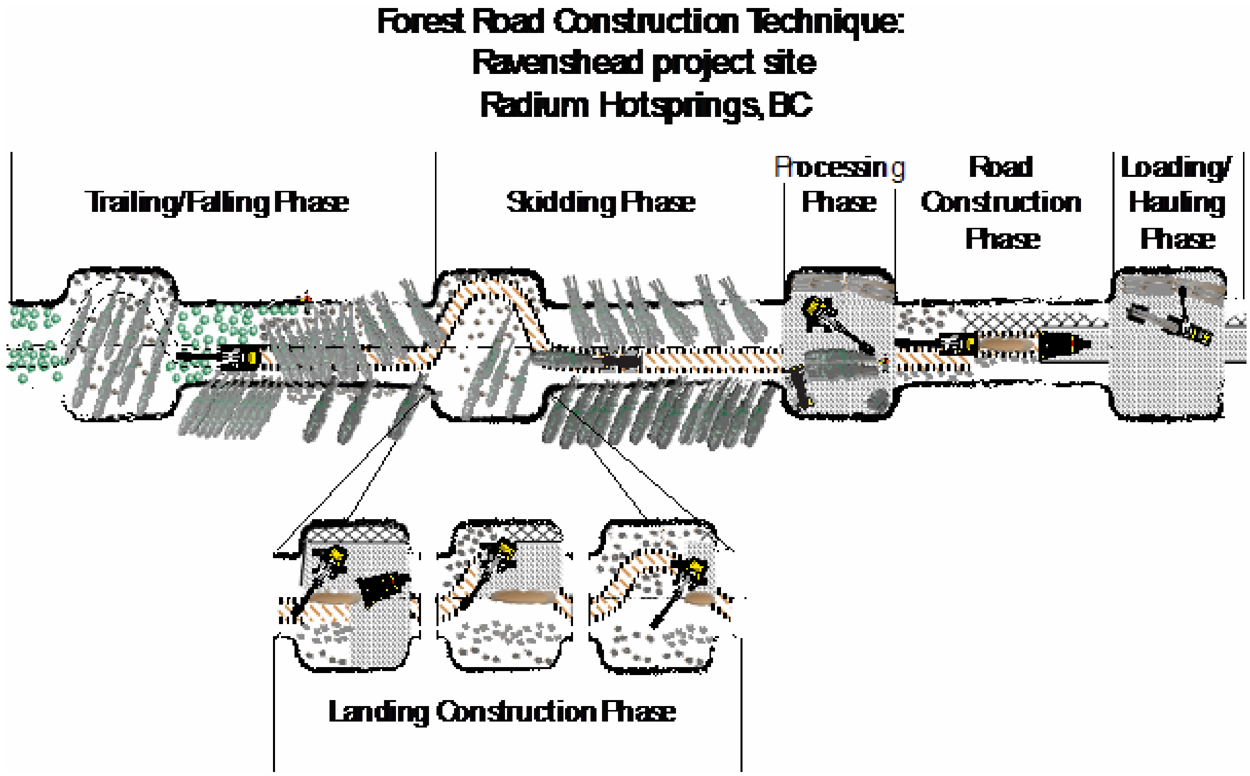

Figure 3. Road construction technique.

4.3 Crew complement

The crew complement for the Ravenshead project consisted of five operators and each had a principal job function. Most of the operators were skilled in more than one job function and could carry out other tasks as needed. The versatility of the operators allowed for much needed flexibility in planning and scheduling the operation.

Leadership and decision-making responsibilities were shared by the road builder and the trailer/faller. One person, known as a utility operator, would switch to any job function as needed. The utility operator was a key individual for this operation because this person could support a particular phase when required and maintain overall road building production. Table 2 shows the principal job functions for each operator and their primary equipment responsibilities.

Table 2. Crew functions and equipment responsibilities

Operator	**Principal job functions**	**Equipment responsibility**
Road builder	Road and landing construction	Excavator (39 000 kg) Bulldozer (26 000 kg)
Trailer/faller	Clear and construct pilot trail, manually fall road clearing width and landing openings	Excavator (22 000 kg)
Skidding operator	Remove wood from clearing width and landings to an established landing for processing	Skidder(s)
Processing operator /bucker	Handle and process stems; skid to finished landing.	Excavator (16 000 kg)
Utility operator	Complete all of the above job functions as required to maintain consistent operations	Operated all of the above equipment

5. FUTURE WORK

The Ravenshead project is the first in a series of case studies investigating different road building techniques and the interaction between the right-of-way logging and road construction activities. Data analysis will be completed in the fall of 2006. A second study, also in southeastern British Columbia, will begin in the summer of 2006.

A longer-term objective of the work is to investigate relationships between equipment productivities and variables such as ground slope and timber type. The results from this project will be combined with future studies to develop a tool for predicting construction productivities and costs based on site variables. This tool will improve road construction planning and contract management.

AVLO: A Simplified Cost Analysis Approach for Estimating Construction Costs for Forest Roads*

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Abstract

Forest roads are a major expense and forest land managers often have problems estimating maintenance, upgrade, and construction costs. In general, road cost estimations are based upon previous personal experiences, machine rate estimations, or acquisition of contractor bids. These techniques can provide acceptable results, but may require more local experience or data requirements than are available to some managers. Therefore, we have developed a relative simple spreadsheet style approach (AVLO) that itemizes the major costs for the common activities for road maintenance, upgrade and construction. Activities evaluated by our program include stream crossings, easements, location, clearing and grubbing, cut and fill slopes, ditching, a variety of water control structures, gravel, seeding, and closure. Cost estimates are based on actual construction costs and logger surveys and are expressed as ranges. The user must have some basic information about desired road standards, road templates, and local terrain. The program also allows the user to modify costs to fit regional costs. The package has been tested on two construction projects and has provided estimates within 5% of actual costs. To date, the approach has been presented to two major forest corporations and the USDA Forest Service and feedback has been positive.

1. INTRODUCTION

Forest roads, ranging from permanent all-weather access to temporary harvest roads, provide access to forest stands for a variety of operations and management objectives. The standards used for each individual road will vary with landowner objectives, Best Management Practices recommendations, site conditions, and many other factors (Aust et al. 2005). The people responsible for road management must take these factors into consideration when looking at specific road standards such as the class or type of road, subgrade, width, ditches, surfacing, cut and fill slopes, gradient and curvature, stream crossings, seeding and closure, etc… (Aust et al. 2005, Walbridge 1997). These may be applicable when building a new road, maintaining or upgrading an existing road, or closing out a road.

Costs associated with managing and implementing proper road standards can have a dramatic affect on a harvesting operation because estimating road costs can often determine the feasibility/profitability of a timber purchase. Unfortunately, many foresters have problems estimating the costs of different road standards, partially due to the lack of published information that actually quantifies costs associated with various road and stream crossing construction activities (Aust et al. 2005, Aust et al. 2003, Aust and Shaffer 2001). In general, road cost

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 165-169.*

estimations are based upon previous experience with costs in an area, estimated machine hours based on published sources, or obtaining contractor bids.

Proper forest road location and construction is important not only to reduce costs, but also to maintain proper water quality (Garland 1987, Kochenderfer et al. 1984, Virginia Department of Forestry 1997, Walbridge 1997). Poorly located and constructed roads are a significant source of sediment from most forestry operations, and additional erosion control measures may be needed to prevent water quality degradation. Preventing erosion from poorly located and constructed roads cost money.

Therefore, researchers from the Industrial Forestry Operations department at Virginia Tech have developed a spreadsheet style approach (AVLO) that itemizes the major costs for the common activities for road maintenance, upgrade and construction. AVLO provides a comprehensive method for capturing all associated components involved in determining road costs, as well as provides a range of values, that are typical for the Southeastern U.S., for each component.

2. SOURCE DATA

AVLO costs were developed based on actual costs reported for road construction and maintenance (Aust and Shaffer 2001), stream crossing installations (Aust et al 2001, 2003), and from surveys of costs encountered by loggers (Shaffer et al. 1998). Additional costs were obtained through personal experiences of the researchers, costs reported by cooperative organizations, and contacts with businesses providing the services or materials associated with road construction and maintenance. This information was used to provide cost ranges for each component of the spreadsheet. Additionally, a "default" cost is provided for each component which represents an approximate average cost for that material or service that is common for the Southeastern U.S.

3. DISCUSSION

AVLO is an Excel based costing system adapted from the itemized planning guide developed by Aust et al. 2005. The user steps through a series of questions identifying the road construction, repair, or maintenance activities that are appropriate for the road under consideration. Average costs are provided for use when the cost of an activity is not known. In the same section, drop-down bars are provided for each activity with a range of costs for use when costs are known. Also, for activities where a quantity or lengths are applicable, spaces are provided for these numbers. Based on the costs and quantity/length of each activity, a total cost is calculated and provided for the user, thus providing a total cost for the road construction, repair, or activity.

In addition to calculating total road cost, a section is available which contains length conversion tables (meter to feet, miles to feet, etc.) and a gravel weight calculator. The gravel weight calculator allows the user to input the dimension of the road and the weight of the gravel being used (a range of weights are provided) in lbs/cubic foot, and will provide the user with an answers in tons of gravel.

Future revisions to AVLO will include ongoing input of costs for various road building activities and expansion of any activities to include more detailed costing features. In addition, as new costing data is received revised AVLO costing spreadsheets will developed to represent different geographical regions of the U.S. such as the Eastern coastal plain, Appalachian region, and the Northwesten U.S. BMP sections will also be added to these spreadsheets to better aid the user.

Overall, AVLO's most beneficial aspect is that it itemizes the majority of costs associated with road construction through a step-by-step method. This ensures the user that all possible activities involved with road construction, repair, or maintenance have been assessed. AVLO does not offer or try to calculate exact costs since they vary dramatically from region to region.

Timber Harvest Road Planning/Cost Estimation Form

Landowner____ General Location____

County/State______________________________________ Date____________________________

Forester____

1. What is the current road situation?

An adequate road exists---------------------------------Stop

No road exists--Proceed to part 2

Road exists, but needs upgrade/repair-------------Proceed to part 5

2. Plan for a new road (or section of road). Locate the desired road on topomap and attach map.

Estimated length of road

Traffic (comment on weight, quantity, and configuration)

Width of Road

Maximum desired grade of road

Permanent or temporary

Rock type & hardness expected (soil survey)

3. Are perennial stream crossings needed?___________ Stream width?______________ Traffic wt?___________

How many of the following are needed?

Type	Length/Quantity	Expected cost range/crossing	Est. Cost	Total
Ford	0	$500-1500/ford	750	0
Reinforced ford	0	$500-2500/ford	1500	0
Culvert (steel or plastic)	0	$400-2000/culvert	1200	0
Portable skidder bridges	0	$2000-10000/bridge	6000	0
Stringer bridges	0	$8000-50000/bridge	29000	0
Other options	0		0	0
4. New Construction Costs				
Easement costs	0	$?	0	0
Location & gradeline installation	0	$500-1500/mile	1000	0
Clearing & grubbing	0	$4000-7000/mile	5500	0
Cut & Fill slopes	0	$1500-2500/mile	2000	0
Ditch construction	0	$1200-2000/mile	1600	0
Shape final surface grade	0	$1000-2500/mile	1750	0
Water control				
broad based dips	0	$25-50/dip	35	0
water turnouts	0	$10-50/turnout	30	0
culvert install & cost	0	$280 install + pipe	0	0
Seeding banks	0	$300-500/mile	400	0
Tons of Gravel	0	$5-30/ton	10	0
5. Upgrade-repair-maintenance-existing road				
Ditch improvement/repair	0	$300-2000/mile	1150	0
Grade road	0	$300-2500/mile	1400	0
Improve water control				
broad based dips	0	$25-50/dip	35	0
water turnouts	0	$10-50/turnout	30	0
culvert install & costs	0	$280 install + pipe	0	0
Seeding	0	$300-500/mile	400	0
Tons of Gravel	0	$5-30/ton	10	0
6. Closure costs				
water bars	0	$15-30/bar	23	0
disc & seed	0	$400-800/mile	600	0
gates	0	$500-2000/each	1250	0
other	0		0	0
7. Other?	0		0	0
TOTAL ESTIMATED COSTS				0

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Robust Optimization of Forest Transportation Networks: A Case Study*

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Abstract
Forest transportation costs are the major cost component for many forest product supply chains. In order to minimize these costs, many organizations have turned to optimization models to guide decisions that are extremely complex in nature. These models generally assume that input parameters are known with certainty, but in reality they are associated with a high degree of uncertainty. One way of dealing with uncertainty is through robust optimization, which is capable of generating near-optimal solutions that are relatively unaffected by the surrounding uncertainty. This we will illustrate by means of a case study that employs a robust optimization approach. Our approach will employ a two phase approach. The first phase will create a more tractable problem by limiting the search to those solutions that are near optimal and feasible. The second phase will simulate the affect of uncertainty on the solutions isolated in the previous phase. The resulting simulation results will then be evaluated for robustness by means of seven robustness performance measures. Our research will show that (1) the deterministic solution is extremely unstable and highly reliant on a particular realization of uncertainty, that (2) the robust solution is dependent on the robust performance measure selected, and (3) that the true robust solution is different from the deterministic solution for our case study.

1. INTRODUCTION

The transportation of forest products from infield locations (stand) to ultimate point of sale (mill) is generally considered to be the foremost cost element of most forestry supply chains. In the southern United States it has been found that these costs can amount to roughly halve of total mill-delivered cost (McDonald et al, 2001). Even in cases where other costly activities such as pruning and pre-commercial thinning were applied, transportation still accounted for 20 to 30% of the discounted seedling to mill cost (Carson, 1989). Minimizing the cost associated with transportation is therefore of paramount importance to the profitability of any forestry organization. This has led to the development of various transport optimization methods and tools through the years. One, the Integrated Resource Planning Model, IRPM (Kirby et al., 1981) is a mixed integer programming model developed for the USDA Forest Service that simultaneously solved the harvest scheduling, road building and transportation problem, but was limited in size due to the number of integer decision variables to represent construction project choices. Others used some form of heuristics. The Timber Transport Model developed by the United States Department of Agriculture (USDA) Forest Service, used a heuristic combination of mixed-integer and network programming to solve the road construction and forest transportation problem (Sullivan, 1974). N-shortest (lowest variable cost) routes were generated using network programming and these became the decision variables for the mixed integer programming

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 171-179.*

problem. Other heuristics using network programming include NETCOST (Weintraub, 1985), NETWORK (Sessions, 1987), and NETWORK 2000 (Chung and Sessions, 2003).

These techniques however all assume that model parameters are known with certainty. The reality however is that most decisions are made under conditions of uncertainty (Wallace, 2000) and that some degree of uncertainty exists as to the true value of model parameters. This is especially true in forest product supply chain problems, where one has to contend with the uncertainty related to harvest age, stand volume, product mix, transportation cost, road cost, mill volumes and market prices. Uncertainty is also not limited to the parameter values, but also extends into the realm of modeling approximation (Wallace, 2000). Every model is an abstraction of the real world. Abstraction requires the generalization of a real world phenomenon in order for it to be squeezed into a particular model. This generalization results in uncertainty, since no model can capture all the detail present in the real world. Models are often also quite complex, resulting in logical modeling errors that are difficult to detect.

In dealing with uncertainty, many practitioners resort to sensitivity analysis to evaluate the sensitivity of a given solution to uncertainty. This approach generates an area of optimality, where a "large" area will point to a stable solution and vice versa (Wallace, 2000). The problem with this technique is that it does not actively search for a stable solution, but merely reports on the stability. Other practitioners have employed worst-case analysis, where parameter values are set to the worst possible expected value. This enables the evaluation of the feasibility of the worst possible outcome, but also leads to sub-optimal and overly conservative results (Sörensen, 2002).

Uncertainty is therefore an unavoidable factor of decision making and optimization, regardless of the industry or discipline. Numerous Operational Research (OR) methods have been developed over the years to deal with uncertainty. These include stochastic linear programming, dynamic programming, and chance constrained methods (Bai et al, 1997). With regards to these techniques, Bai et al notes that "despite the presence of uncertainty in critical real-world problems, optimization based systems on the whole fail to address risk aversion as specified in classical decision theory" (Bai et al, 1997). That is, these techniques do incorporate uncertainty, but do not necessarily minimize the effects of the uncertainty.

This is exactly where the strength of robust optimization lies, since its goal is to find a "near optimal solution that is not overly sensitive to some realization of uncertainty" (Bai et al, 1997). Robust solutions therefore have two distinguishing characteristics. First, they are close to optimal (Mudchanatongsuk, 2005), where the degree of optimality is referred to as "absolute robustness" (Carr et al, 2006). Second, they exhibit limited deviation from a given robust solution under considered variation, a condition known as "robust deviation" (Carr et al, 2006).

In this paper, we present a two-step procedure for finding robust solutions to real-world forestry transportation problems. We will also present seven different measures of robustness and will highlight how these measures influence the ultimate decision through a case study. The most similar work in this area was reported by Moore (1987) and Moore et al. (1988) who examined the sensitivity of transportation solutions to changes in fixed and variable costs for several network algorithms.

2. METHODS

We will begin this section with a description of the chosen study area. This will be followed by discussion of the two-step robust optimization technique and subsequent robustness evaluation measures.

2.1 Study Area

The area selected for this study is a small plantation forest called Tainui-Kawhia, located on the west coast of New Zealand's north island. The landholding has an area of ±900 ha, of which ±895 is planted to *Pinus radiata*. Data was originally collected in the 1980's for use in a New Zealand forest industry workshop on forest transportation analysis. The area has subsequently been harvested.

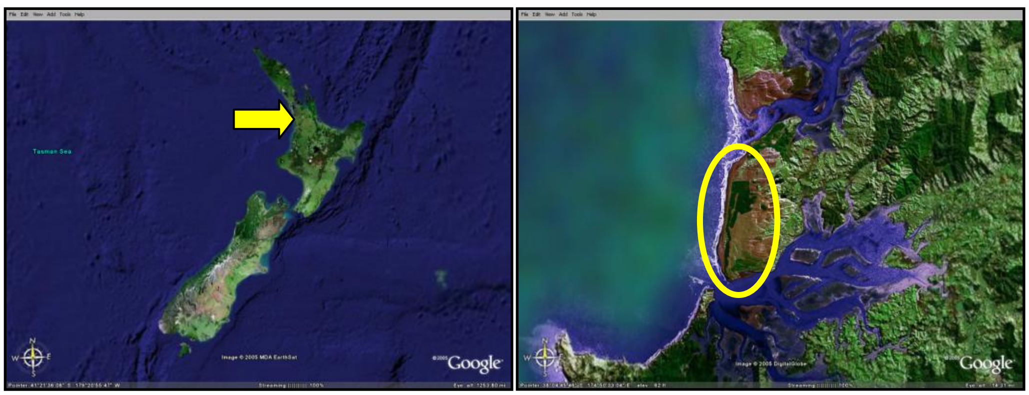

Figure 1: Geographic location of study area. Left: Context view of location of Tainui-Kawhia on New Zealand's north island. Right: Extent of Tainui-Kawhia.

Harvest age ranged from 25 to 31 years, and the total expected volume over an 11 year harvest period was expected to be 391,000 m³. The coefficient of variation for total volume was set at 2.5%. Since the silvicultural regime included pruning and pre-commercial thinning, this area is capable of producing pruned veneer logs, pruned saw logs, un-pruned saw logs and pulp logs. It was expected that these products would respectively represent 10%, 24%, 55% and 11% of the total volume. The coefficients of variation for these percentages were respectively set at 12.5%, 7.5%, 5.0% and 12.5%.

Six possible markets existed for the logs, which were located in Auckland, Hamilton, Tokoroa, Taumaranui, New Plymouth and Wellington. Veneer logs were accepted by mills located at Auckland, Tokoroa or Wellington. Pruned saw logs were accepted by mills at all six locations. Un-pruned saw logs were accepted by all mill locations, except Wellington. Pulp logs were only accepted by the mill located at Tokoroa. Mill-delivered prices for these respective products were US\$83/m³, US\$66/m³, US\$40/m³ and US\$33/m³ (1 US\$ = 1.5 NZ\$). The respective coefficients of variation for these prices were 6.67%, 6.67%, 11.11% and 6.67%.

Since the plantation was established on flat coastal sand dunes, the entire area could be harvested with ground based systems. The original road infrastructure was constructed to a standard that facilitated light use for silvicultural and management purposes. The road system therefore had to be upgraded to consider logging transportation. In addition, ±70 landings had to be constructed. The internal transportation network linked with the external transportation network at three locations; an existing road exit at the south end of the plantation, a proposed coastal marine barge exit at the south end of the plantation (a log storage and barge loading facility had to be constructed), and a proposed road exit at the north-east corner of the plantation (right-of-way had to be purchased and a linking road constructed).

From these exit points, three alternative transportation options existed:

- Truck all the way to the mill
- Barge to either Auckland or New Plymouth, followed by truck to the mill
- Truck to a rail loading facility, rail to an unloading facility, truck to the mill

Tokoroa was the only mill with direct linkage to a rail network. Transport cost elements and associated coefficients of variation were as follows:

Table 1: Estimates of transport cost elements and their associated coefficients of variation.

Cost Type	Cost Element	Cost	Coefficient of Variation (%)
Variable Costs	Log and Load	US$8/m³	15.0
	Road Transport	US$0.14/m³/km	7.5 to 20
	Rail Transport	US$7/m³ to US$37/m³	5.5 to 6.5
	Rail Load	US$1.33/m³	±3.5
	Barge Transport	US$8/m³ to US$9/m³	±5.0
	Barge Load and Unload	US$4/m³ to US$5/m³	±2.5
Fixed Costs	Landings	US$8,400	±20.0
	Roads	US$4,600/km to US$18,800/km	±20.0
	Barge Landing	US$70,000	±6.5

2.2 Robust Optimization Procedure

The robust optimization procedure that will be proposed here has two distinct phases, namely the scenario generation phase and the scenario evaluation phase. During the scenario generation phase 100 trials were performed on the input data to isolate a set of candidate robust solution scenarios. First step was to create ten unique transportation networks from the original network, by allowing the variable and fixed costs of each network link to deviate a random number of standard deviations from the mean. Next, ten sets of sales volumes were created by allowing the overall stand volume and product mix of each stand to deviate a random number of deviations from the mean. In both cases, the deviations were limited to 3 standard deviations from the mean along an assumed normal distribution. Then, by pairing the set of ten transport networks with the set of ten sales volumes, 100 unique trials were generated. Network 2000, a heuristic network analysis package (Chung and Sessions, 2003), was then used to determine the optimum transport mode, route and sales destination for each trial. Optimality was based on maximized NPV, using a discount rate of 7%. The 100 solutions obtained were then grouped into similar solutions, with similarity defined as those solutions that sent the same products to the same destination via the same transport mode. This rendered the overall problem more tractable, since it was reduced to those candidate solutions that were both feasible and potentially optimal. This step is especially important when dealing with real-world problems, since the complexity contained therein can often render the problem both computationally and logically difficult to solve.

During the scenario evaluation phase, each of the candidate scenarios identified above were subjected to a set of 1,000 simulations. For each simulation the variable and fixed cost of each network link was randomly varied, as well as the total volume and product mix of each stand. Once again deviations were limited to 3 standard deviations from the mean along an assumed normal distribution. The 1,000 trials for each scenario were then used to calculate the scenario's robustness, based on seven robustness performance measures.

In addition to the above, the NPV of the optimal deterministic solution was also determined. This was established by using the means of all input parameters in Network 2000.

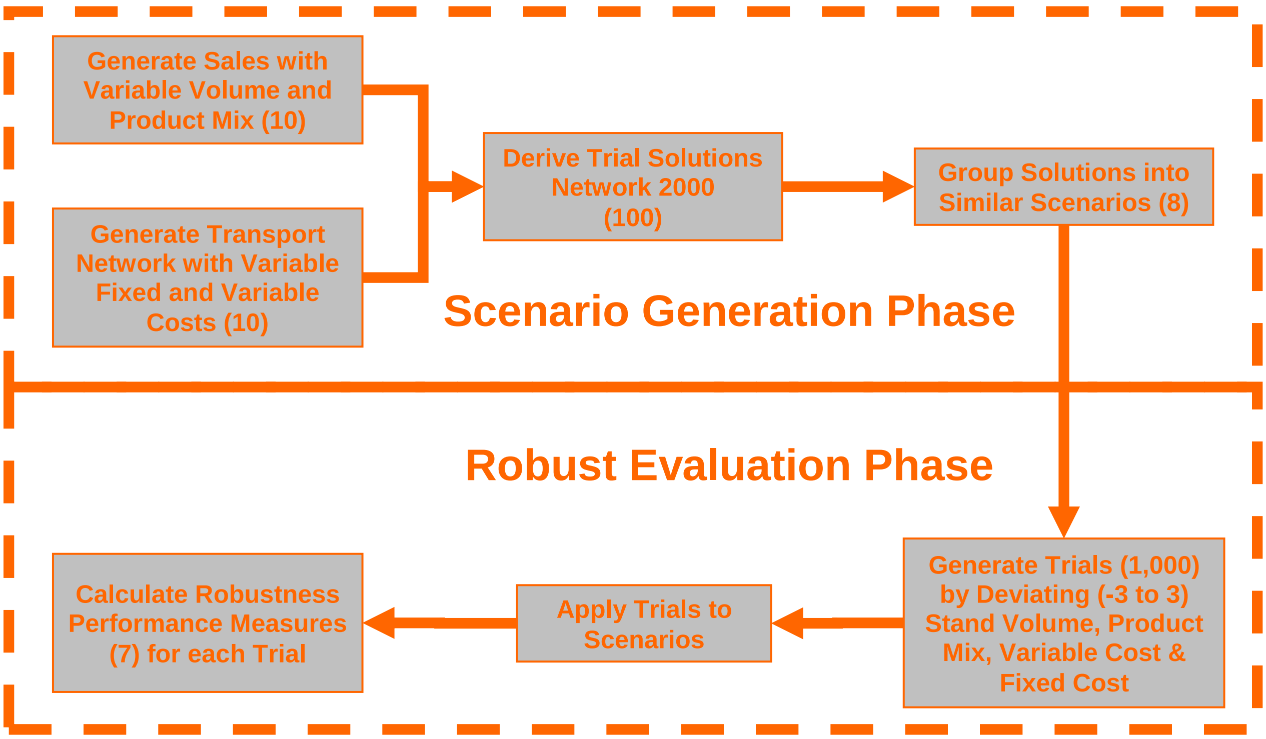

Figure 2: Schematic of robust optimization procedure used with this case study

2.3 Robustness Performance Measures

In order to ascertain the robustness of each candidate scenario, seven robustness performance measures were evaluated. The first performance measure was calculated from data collected during the scenario generation phase, while the rest was calculated from the scenario evaluation phase data. They were:

- Most Frequent Solution: Candidate scenario that was found to be optimal by Network 2000 the highest number of times.
- Highest Average NPV: Candidate scenario that had the highest average NPV.
- Lowest Variation in NPV: Candidate scenario with the lowest standard deviation from the average NPV.
- Best Worst-Case NPV: Candidate scenario with the highest minimum NPV.

- Highest NPV Signal-To-Noise Ratio: Candidate scenario with the highest ratio of average NPV to NPV standard deviation.
- Highest Weighted NPV Sum: Candidate scenario with the highest normalized and weighted sum of average NPV and NPV standard deviation. Weights of 0.75 and 0.25 were applied to the normalized average NPV and NPV standard deviation.
- Lowest Threshold Probability: Candidate scenario with the lowest probability to yield a solution value less than a predetermined threshold value. The threshold was set to 95% of the NPV for the deterministic solution.

3. RESULTS

The scenario generation phase identified ten unique candidate scenarios. Two of these were near similar to two others with respect to markets supplied, transport modes and routes taken. These were subsequently grouped together, resulting in eight candidate scenarios being taken forward to the scenario evaluation phase. These will be labeled scenarios 1 to 8 for future reference.

Following the scenario evaluation phase, only two scenarios (1 and 3) displayed strong robustness as measured by the seven robustness performance measures. Scenario 1 had the highest average NPV (US$5.552 million), best worst-case NPV (US$5.334 million) and lowest threshold probability (15.1%). It equaled scenario 4 with respect to the most frequent solution (20). It was also identical to the deterministic solution with regards to markets supplied, transport modes and routes taken.

Scenario 3 however ranked best in the three remaining robustness performance measures. It had the lowest NPV standard deviation (US$0.196 million), highest NPV signal-to-noise ratio (27.43) and the highest weighted NPV sum (0.975). Scenario 3 persisted to have the highest weighted NPV sum until the weights were changed to 0.90 and 0.10, after which scenario 1 had the highest value.

Table 2: Robustness performance measures evaluated for the eight scenarios examined in the scenario evaluation phase.

Performance	Scenario							
Measure	1	2	3	4	5	6	7	8
Most Frequent Solution (%)	20	10	10	20	10	10	10	10
Highest Average NPV (US$ millions)	5.552	5.490	5.365	5.335	4.952	4.923	4.838	4.729
Lowest Variation in NPV (US$ millions)	0.275	0.293	0.196	0.334	0.371	0.249	0.598	0.762
Best Worst-Case NPV (US$ millions)	5.334	5.245	5.065	4.941	4.426	4.663	3.868	3.997
Highest NPV Signal-To-Noise Ratio	20.23	18.74	27.43	16.00	13.35	19.75	8.10	6.20
Highest Weighted	0.928	0.908	0.975	0.867	0.801	0.861	0.735	0.703

NPV Sum								
Lowest Threshold Probability	15.5	23.1	32.1	42.7	80.7	92.0	76.7	76.3

In addition, scenario 1 and 3 were substantially different with regards to markets supplied, transport modes and routes. With scenario 1 veneer logs would be sent by barge to Auckland, pruned and un-pruned saw logs would be sent by road to Hamilton and pulp logs would be sent by road to Tokoroa. In this scenario about 10% of the volume would be transported by barge and 90% by road.

For scenario 3 veneer logs, pruned saw logs and about one third of un-pruned saw logs would be transported by barge to Auckland. The remaining un-pruned saw logs would be transported by road to Hamilton, while the pulp logs would be transported by rail to Tokoroa. In this scenario about 54% of the volume would be transported by barge, 35% by road and 11% by rail.

4. DISCUSSION

The management of forestry enterprises requires the simultaneous consideration of numerous supply chain factors to remain cost efficient and competitive. This is especially true for transportation optimization, since the selection of the optimal practice is contingent on factors ranging from harvest age through to mill demands. In this study we evaluated the effect of stand volumes and product mixes, the variable and fixed costs associated with various transport modes, and mill revenues. To consider all of these factors at once, many practitioners are turning to various optimization models. These models however typically do not account for the variation and uncertainty that is inherent to the practice of forestry. These uncertainties can however have a profound effect on the ultimate optimal solution, and by using robust optimization, decisions can be made that are substantially more immune to uncertainty.

Our first finding from this study was that uncertainty can give rise to numerous solutions that seem optimal. This was evident in the fact that our deterministic solution procedure (scenario generation phase) delivered eight distinctly different solutions when the expected input values were varied. The optimal solution of our case study was therefore highly sensitive to variations in the input data (uncertainty) and therefore unstable. This is hardly a desirable situation, since a minor error in input data could lead to the wrong transport strategy being selected.

Our second finding was that the robust solution is dependent on the selection of robust performance measure. Here we evaluated seven robustness measures, and found that they isolated two potentially robust solutions (scenario 1 and 3). To isolate the most robust solution we need to return to the principles of robust optimization, and isolate those robust performance measures that truly adhere to those principles. Robust solutions typically display two characteristics. They are near-optimal (absolute robust) and display a low degree of deviation from their mean value under uncertainty (robust deviation, low regret) (Bertuccelli et al, 2004) (Carr et al, 2006). It is the combination of these two characteristics that constitutes the definition of a truly robust solution. In this regard, we found that scenario 1 only displayed absolute robustness, since it only ranked high with those measures that were contingent on the absolute value of the NPV. Scenario 3, on the other hand, displayed both absolute robustness and robust deviation, since it ranked highest with those measures that incorporated both the absolute NPV and its standard deviation. Of particular interest is the high ranking of scenario 3 with regards to the signal-to-noise robust performance measure, since this ratio is often used in practice to evaluate robustness (Al-Aomar, 2002) (Chen et al, 1999). We can therefore conclude that scenario 3 is the most robust of all the scenarios evaluated.

Our third, and final, finding was that our inclusion of uncertainty in the optimization process for our case study did lead to a different solution than the deterministic solution. Scenario 1 was the deterministic solution for this study. However, by incorporating a measure of robustness our optimal solution was scenario 3.

Robust optimization is therefore an optimization technique that could lead to better decision making in forestry. Much work however remains to be done. First, future studies should investigate the scenario generation phase employed in this study. Its purpose was to break the problem down to a more tractable one, but limiting the scenario generation to a pool of 100 candidates could have narrowed the search down prematurely. Larger pools, or other techniques to isolate candidates, should be investigated. Also, whenever heuristics are used to solve a problem, caution must be used in interpreting solutions. Heuristic rules may trap solutions in a local optimum over a range of inputs thus underestimating variances in solutions as well as underestimating the optimal value of the deterministic solution. Second, it was assumed that all parameters varied along a normal distribution from the mean. However, normal distributions might not adequately describe the actual distributions. Other distribution forms and their affect on overall results should therefore also be investigated. Third, the model should be expanded to incorporate the effect of additional supply chain factors. These might include placing an upper and lower limit on mill demand, and varying the final harvest age of stands. Fourth, the source and cost of uncertainty could be examined. For example, the origin of uncertainty about log prices may be different than the uncertainty concerning road, landing, and harvest costs. Log prices may depend on exogenous factors, while the variation in road, landing, and harvest costs may be dependent upon the quality of planning. Therefore the source of the uncertainty may need to be examined.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Using Ant Colony Optimization Metaheuristic in Forest Transportation Planning*

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Abstract
Timber transportation is one of the most expensive activities in forest operations. Traditionally, the goal of forest transportation planning has been to find the combination of road development and harvest equipment placement that minimizes total harvesting and transportation costs. However, modern transportation problems are not driven only by economics of timber management, but also by multiple uses of roads and their social and ecological impacts. These social and environmental considerations and requirements introduce side constraints into the forest transportation planning, making the problems larger and more complex. We developed a new problem solving technique using the ant colony optimization (ACO) metaheuristic, which is able to solve large and complex transportation planning problems with side constraints. We considered the environmental impact of forest road networks represented by sediment yields as side constraints. Results on a hypothetical transportation problem show that this algorithm (ACO-FTPP) is promising for solving real forest transportation planning problems with side constraints. A description of the development of the algorithm and its search process is presented.

Keywords: forest transportation planning, ant colony optimization metaheuristic, forest road networks, sediment minimization

1. INTRODUCTION

Problems related to forest transportation planning have long been an important concern due to the fact that timber transportation is one of the most expensive activities in forest operations (Greulich 2002). Traditionally, the goal of forest transportation planning problems (FTPP) has been to find the combination of road development and harvest equipment placement that minimizes total harvesting and transportation costs. However, modern FTPP are not driven only by the economics of timber management, but also by multiple uses of roads and their social and ecological impacts such as recreation, soil erosion, wildlife and fish habitats among others. These environmental and social considerations and requirements introduce side constraints to the FTPP, making the problems larger and more complex.

Two different approaches have been applied to solve FTPP: exact algorithms such as mixed-integer programming (MIP), and approximation algorithms generally called heuristics (Falcao 2001; Weintraub 1995). The most important advantage of exact algorithms is that they provide optimal solutions. However, they are limited to small scale problems. Contrarily,

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 181-191.*

heuristic techniques, although may not provide optimal solutions, have successfully been applied to solve large scale problems and are relatively easy to formulate compared with exact algorithms (Olsson 2003; Martell et al 1998; Weintraub 1995). Since real world transportation problems are usually large scale problems with thousands of variables, heuristic techniques have been the focus of a large number of researchers (Zeki 2001).

The case of FTPP with fixed and variable costs form complex optimization problems that to date have only been solved efficiently using heuristic approaches. NETWORK II (Sessions 1985) and NETWORK 2000 (Chung and Sessions 2003), which use a heuristic approach combined with the shortest path algorithm (Dijkstra 1959), have been widely used for the last twenty years. NETWORK 2000 can solve multi-period, multi-product, multi-origin and -destination transportation planning problems, but it considers only either profit maximization or cost minimization without taking into account other attributes of road links. NETWORK 2001 (Chung and Sessions 2001) was developed to solve multiple objective transportation planning problems by combining the shortest path algorithm with a simulated annealing heuristic. NETWORK 2001 allows users to modify the objective function to evaluate solutions considering multiple objectives, but currently does not allow having side constraints.

Because heuristic approaches usually do not guarantee the optimality of solutions, testing different heuristic approaches has been a constant effort of numerous researchers. New heuristics and hybrids of existing heuristics are continually being developed, but only a few algorithms have been applied to FTPP having both fixed and variable costs. One of the promising algorithms not yet applied to FTPP is the Ant Colony Optimization (ACO) metaheuristic, an optimization technique introduced in 1991 by Dorigo and colleagues (Dorigo 1999a). To date there have been numerous applications of ACO metaheuristic developed to solve a number of different combinatorial optimization problems. Currently, some ACO algorithms have provided the best known results for solving many of the most important combinatorial optimization problems (such as the traveling salesman problem (TSP), quadratic assignment problem (QAP), job-shop scheduling problem (JSP), vehicle routing problem (VRP) among others), while others have matched the results of the best known algorithms (Dorigo 2002; Dorigo1999a).

ACO algorithms are inspired by the observation of the foraging behavior of real ant colonies, and in particular, by how ants can find shortest paths between food sources and the nest. When walking, ants deposit a chemical substance on the ground called *pheromone*, ultimately forming a pheromone trail. While an isolated ant moves essentially at random, an ant that encounters a previously laid pheromone trail can detect it and decide with a high probability to follow it, therefore reinforcing the trail with its own pheromone. This indirect form of communication is called *autocatalytic* behavior, which is characterized by a positive feedback, where the more ants following a trail, the more attractive that trail becomes for being followed (Dorigo 1999b).

The ACO metaheuristic approach is promising for solving FTPP with fixed and variable costs for the following reasons: *i)* the inspiring concept of ACO metaheuristic is based on a transportation principle, and it was first intended to solve transportation problems that can be modeled through networks, *ii)* its effectiveness in finding good solutions to difficult optimization problems, as introduced in the literature, and *iii)* the nature of the FTPP, which allows the problem to be modeled as a network problem.

In this paper, we introduce ACO-FTPP, a specially designed ACO algorithm for solving FTPP with fixed and variable costs while considering total sediment yields from the road network as a side constraint. A description of the ACO-FTPP algorithm and its search process are presented.

2. METHODOLOGY

2.1 Problem Formulation

The FTPP we address in this paper is finding the set of least cost routes from multiple timber sales to selected destination mills, while considering environmental impacts of forest road networks represented by sediment yields. As most of transportation problems, these FTPP can be modeled as network problems. The road system is represented by a graph *G*, where vertices represent destination points (i.e. mill locations), entry points (i.e. log landing locations), and intersections of road segments, while edges represent the road segments connecting these different points. The graph *G* has three variables associated with every edge; fixed cost, variable cost, and the amount of sediment.

The transportation network may be composed of existing and/or proposed roads. Fixed cost for an existing road segment could either be zero or a fixed maintenance cost for the road segment. In the case of proposed roads, fixed cost represents the construction cost of the road segment plus fixed maintenance. Fixed cost is a one-time cost which occurs if the road segment is used. Variable cost refers to the hauling cost. Unlike the fixed cost, variable cost is proportional to traffic volumes. Although there are several ways to estimate the unit variable cost ($/vol-edge), in most cases it is a function of the road length, driving speed, and operating costs (Byrne at al 1960, Moll and Copstead 1996). Since every road segment has different conditions, there will be a different unit variable cost associated with each edge. The sediment associated with each edge represents the amount of sediment eroding from the road segment in tons per year per edge. Like fixed cost, we assumed that sediment is produced when roads are open regardless of the traffic volume. The WEPP model can be used to estimate average annual sediment yields from each road segment (Elliot et al 1999). In addition to the three variables related to each edge, it is also required to have the total volume of wood per timber sale to be delivered to the selected mill location.

In this context the problem under consideration is to find the transportation routes that minimize the combination of fixed and variable costs (Eq. 1) subject to a sediment yield restriction (Eq. 2).

$$\text{Minimize} \quad \sum_{i=1}^{e}\left[\left(var\_cost_i * vol_i\right) + \left(fixed\_cost_i * B_i\right)\right] \qquad \text{[Eq. 1]}$$

$$\text{Subject to} \quad \sum_{i=1}^{e}\left(sediment_i * B_i\right) \leq allowable\_sed \qquad \text{[Eq. 2]}$$

where,

var_cost_i	: variable cost for edge *i* in $/vol.
$fixed\_cost_i$	: fixed cost for edge *i* in $.
$sediment_i$	: amount of sediment eroding from edge *i* in tons.
vol_i	: total volume transported over edge *i*

B_i	: binary variable (1 if edge is used and 0 otherwise)
e	: total number of edges in the network
$allowable\_sed$	: maximum allowable sediment in tons

2.2 Ant Colony Optimization Metaheuristic

In ACO metaheuristic a colony of *artificial ants* is set to find good feasible solutions to combinatorial optimization problems. Computational resources are allocated to relatively simple agents – *artificial ants*. These *artificial ants* have a double nature. On one hand, they are the abstraction of those behavioral traits of real ants, which seem to control the shortest path finding ability. On the other hand, they are enriched with some capabilities not present in their natural counterparts (Dorigo 1999a).

There are four main ideas taken from real ants (Dorigo 1999a, 1999b); the use of: *i) colony of cooperating ants* – high quality solutions emerge as a result of the interaction of the entire ant colony, *ii) pheromone trail and indirect communication* – artificial ants change some numerical information stored in the problem' stage they visit, *iii) shortest path searching and local moves* – artificial ants have the purpose of finding the shortest path moving step by step, and *iv) stochastic and myopic state transition policy* – artificial ants move through adjacent states applying a probabilistic decision policy.

To increase the efficiency and efficacy of the colony, some enriching characteristics have been given to artificial ants. Some of these characteristics are that artificial ants *i)* live in an environment where time is discrete, *ii)* have an internal state, which contains the memory of the ants' previous actions, *iii)* deposit an amount of pheromone proportional to the quality of the solution found, and *iv)* are not completely blind and can incorporate look-ahead information, local optimization and backtracking to improve overall system efficiency.

In ACO algorithms, ants moves through adjacent states of the problem applying a stochastic transition policy that considers two parameters called *trail intensity* and *visibility*. Trail intensity refers to the amount of pheromone in the path and visibility is usually computed as some heuristic value such as cost or distance (Maniezzo 2004). Therefore, moving through adjacent steps, ants incrementally build a feasible solution to the optimization problem. Once an ant finds a solution, it evaluates the solution and deposits pheromone on the connections it used, proportionally to the goodness of the solution. Ants can deposit pheromone on a connection either directly after the move is made without waiting for the end of the solution or after a solution is built by retracing the same path backwards (Dorigo 2002).

2.3 ACO-FTPP algorithm

ACO-FTPP is the specialized ACO algorithm we developed to solve the FTPP described. ACO-FTPP has a finite number of ants (m) that search for r least cost paths, one from each timber sale-destination pair. After a certain number of transitions from vertex to vertex, an ant arrives at its destination thus completing a *route*.

When an ant is located on a given vertex, it has to choose where to go based on a transition probability for each adjacent edge, which is calculated by the following equation (Eq. 3).

$$\rho_j(c) = \frac{(\tau_j)^\alpha * (\eta_j)^\beta}{\sum_{i=1}^{l} (\tau_i)^\alpha * (\eta_i)^\beta} \qquad \text{if } j \in \mathrm{N}_l \qquad \text{[Eq. 3]}$$

where, $\rho_j(c)$ indicates the transition probability with which an ant, chooses the edge *j* in *iteration c*; *l* is the number of edges in the set N_l sharing the same origin vertex; α and *β* are the parameters that control the relative importance of the pheromone trail intensity (τ_j) and the visibility (η_j) values on edge *j*. The visibility value is calculated according to the following equation (Eq. 4).

$$\eta_j = \left(var\_cost_j * vol_s\right)^{-1} * fixed\_cost_j^{-1} * sediment_j^{-1} \qquad \text{[Eq. 4]}$$

Consequently, by combining equations 3 and 4, the resulting transition probability formula for a given edge is determined as follows:

$$\rho_j(c) = \frac{\left(\tau_j\right)^\alpha * \left(\left(var\_cost_j * vol_s\right)^{-1} * fixed\_cost_j^{-1} * sediment_j^{-1}\right)^\beta}{\sum_{i=1}^{l} \left(\tau_i\right)^\alpha * \left(\left(var\_cost_i * vol_s\right)^{-1} * fixed\_cost_i^{-1} * sediment_i^{-1}\right)^\beta} \quad \text{if } j \in \mathrm{N}_l \quad \text{[Eq. 5]}$$

Based on the transition probability values of all edges in N_l, accumulated transition probabilities for each of these edges are computed. Then, a random number between zero and one is selected using a random number generator. If this random number is smaller than the accumulated transition probability of edge *i* and larger than the accumulated transition probability of edge *i-1*, then edge *i* is selected.

Starting from a given timber sale and ending on the selected mill destination, an ant incrementally builds a *route*, moving through adjacent edges according to the transition probability equation (Eq. 5). When all ants have found a route, the best *route* among the *m* generated by the *m* ants is selected as the *least cost path*. Then, ants move to the next randomly selected timber sale to find the *least cost path*. When all timber sales have been routed to their destination mills an *iteration* is complete, all the edges forming all *least cost paths* (one for every sale-destination pair) are identified, the objective function value is computed and the solution feasibility is evaluated. If the current solution is not better than the best found so far or is infeasible, the solution is ignored, the pheromone trail intensities remain the same and another *iteration* starts. However, if the current solution is better than the best solution found so far, the current solution becomes the new best solution and the pheromone trail intensity of the edges forming all *least cost paths* is updated. At the same time, pheromone intensity on all edges decreases (evaporates) in order to avoid unlimited accumulation of pheromone. Also pheromone evaporation avoids a too-rapid convergence of the algorithm towards a sub-optimal solution, allowing the exploration of other solution spaces. Pheromone trail intensity is updated using the following equation (Eq. 6):

$$\tau_i(c+1) = \lambda * \tau_i(c) + \Delta\tau_i \qquad \text{[Eq. 6]}$$

where two components are considered; the current pheromone trail intensity on edge *i* at *iteration c*, indicated by $\tau_i(c)$, multiplied by $0 < \lambda < 1$ which is a coefficient such that $(1 - \lambda)$ represents the pheromone evaporation rate between *iteration c* and *c + 1*; and $\Delta\tau_i$ which represents the newly added pheromone amount to edge *i*, calculated as follows:

$$\Delta\tau_i = \sum_{k=1}^{s} \Delta\tau_i^k \qquad \text{[Eq.7]}$$

where, *s* is total number of timber sales, and $\Delta\tau_i^k$ is the quantity of pheromone laid on edge *i* by the ants in *iteration c*; which is given by:

$$\Delta\tau_i^k = \begin{cases} Q / L_k & \text{if the ants used edge } i \text{ in the } \textit{shortest path} \\ 0 & \text{otherwise} \end{cases} \qquad \text{[Eq. 8]}$$

where *Q* is a constant and L_k is the total transportation cost over the selected *route*. The value of *Q* has to be chosen so the amount of pheromone added to edge *i* by a given ant slightly increases the probability of that edge during the following iterations.

Given the definitions above, ACO-FTPP can be stated as follows (see Figure 1). At *iteration* 1 an initialization phase takes place in which ants start at a random timber sale location. An initial equal small amount of pheromone *q* is set for each edge, and transition probabilities for each edge are computed considering the volume of the chosen timber sale. Thereafter each ant can find a *route* by moving through adjacent edges until the mill destination is reached.

When an ant moves through an edge, the edge is recorded with its from- and to- vertex in the ant's internal memory. This memory is used to avoid ants returning to a previously visited vertex. When an ant is located at a vertex whose all adjacent vertices have been previously visited, it stops without reaching its destination and a high cost is assigned to the ant's route as a penalty. Likewise, if an ant has not found its destination after a maximum number of moves *Max_moves*, the ant stops and a high cost is assigned. For applications currently being tested, the *Max_moves* is set to be the number of vertices in the network plus one (*v* + 1).

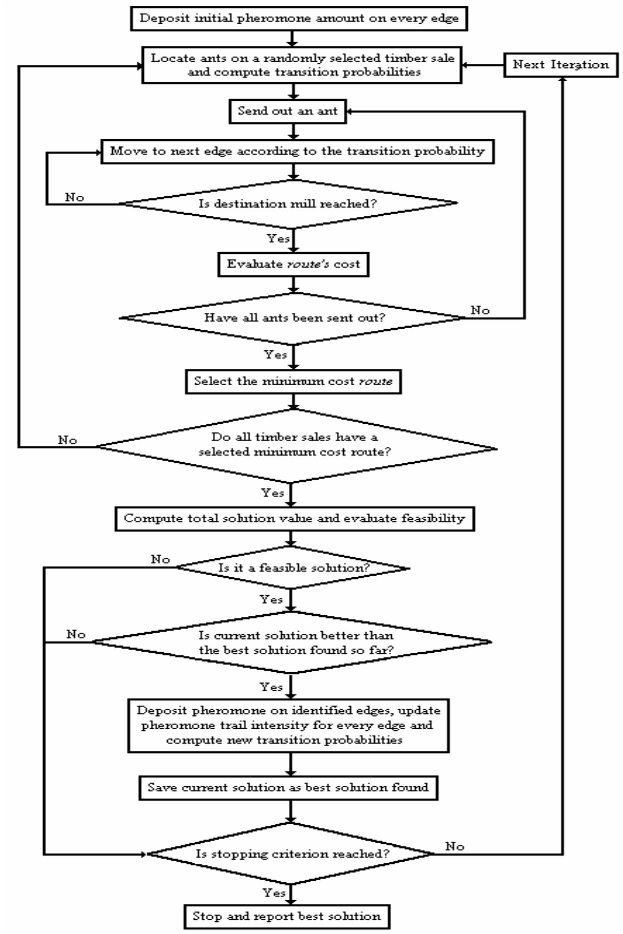


Figure 1. Flowchart of the ACO-FTPP search process

2.4 Setting Parameters

ACO-FTPP requires values for the parameters α, β, λ, q, Q, m, and I_{max}. Our initial test runs of ACO-FTPP confirmed the findings of previous studies that different parameter combinations affect the performance of the ACO (Dorigo et al 1996). Thus, we conducted a search for the best parameter combination. Because more than one parameter combination can reach the same quality solution, to select the best parameter combination we consider the number of iterations taken to find the best solution as well as solution quality.

Three of the seven parameters required by ACO-FTPP (q, m, and I_{max}) do not affect the calculation of the transition probability (Eq. 3 - 8). Therefore these parameter values were fixed in our trials. For our applications, q was set to 0.001,. m was set equal the number of edges (e), and I_{max} was set to 100 to give the algorithm enough time to find the best solution.

The parameters Q, α, β, and λ, directly affect the calculation of the transition probability (Eq. 3 - 8), therefore they may significantly affect the performance of the algorithm. The constant Q, related to the quantity of pheromone deposited by ants, has to be chosen so the transition probability of an edge from one iteration to the next is slightly increased. Because initial test runs showed that Q do not have a significant effect on the solution quality, we set Q to

0.001. The remaining parameters (α, β, and λ) were identified to directly affect the performance of the algorithm, and therefore subject to the search for the best parameter combination.

To test different values of the parameters α, β, and λ, a range for each parameter was defined and partitioned into ten, fifteen, and ten discrete values respectively. The tested values for α were from 0.5 to 9.5 in increments of 1.0. For β we tested values from 0.5 to 14.5 in increments of 1.0. Lastly, for λ the values tested were from 0.05 to 0.95 in increments of 0.1. This yielded 1,500 different parameter combinations. After applying ACO-FTPP in initial test runs the best parameter combination found by this search was α = 1.5, β = 0.5 and λ = 0.65.

2.5 Hypothetical Transportation Problem

To examine the behavior and performance of the algorithm, ACO-FTPP was applied to a 25-edge hypothetical FTPP (see Figure 2). This problem includes three timber sale locations, represented by nodes 1, 2 and 3 respectively, and one destination mill, indicated by node 12. Timber sales 1, 2 and 3 have a total volume of timber to be delivered of 983, 1278, and 901 units of volume. In Figure 2, there are three variables associated with each edge: variable cost, fixed cost, and amount of sediment are indicated by the top, middle, and bottom numbers respectively.

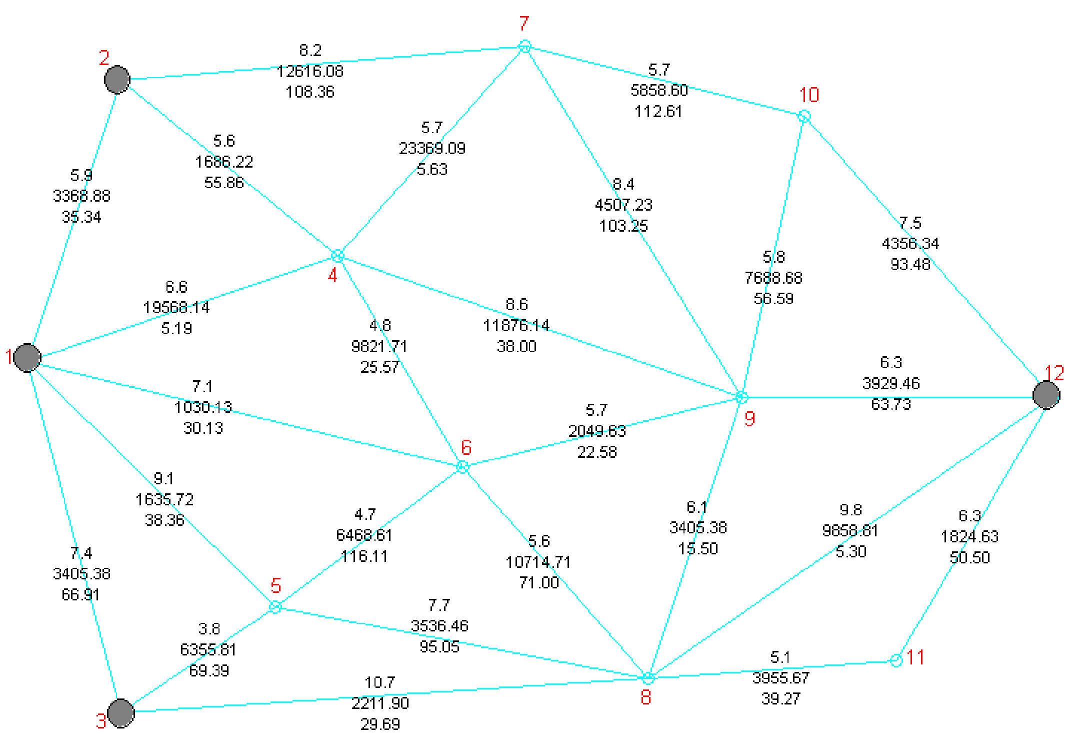
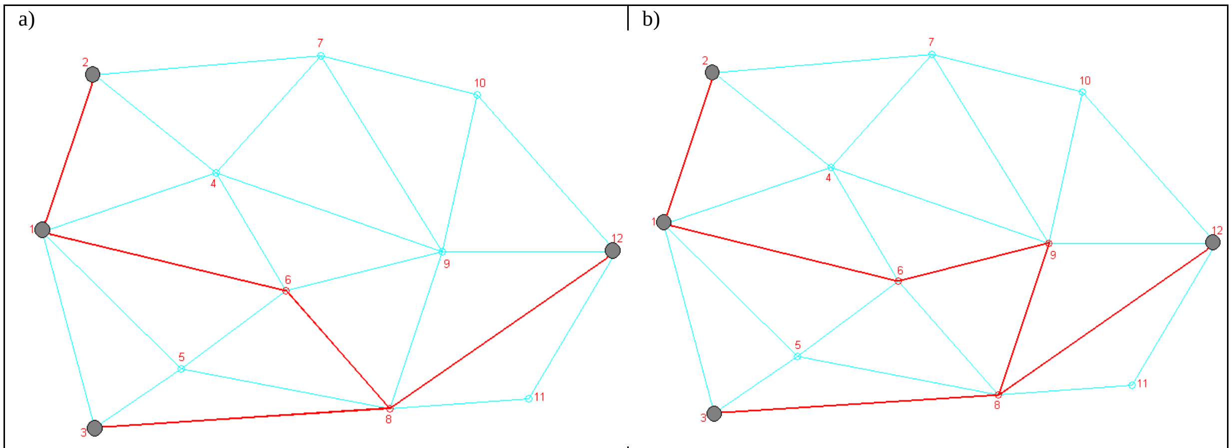


Figure 2. Hypothetical forest transportation problem with 25 edges, three timber sales and one destination mill.

3. RESULTS

Two different cases with a different level of sediment restriction were analyzed to test the ACO-FTPP algorithm. *Case I*: a cost minimization problem considering a sediment restriction of 180 tons, and *Case II*: a cost minimization problem considering a sediment restriction of 150 tons. The sediment restriction values were chosen based on the sediment amount associated with the solution of the cost minimization problem without sediment restriction.

The best solution found by ACO-FTPP for *Case I* has an objective function value of \$109,195 (\$34.54/vol) with an associated sediment amount of 179.69 tons. For *Case II*, the best solution found by ACO-FTPP reached a minimum total cost of \$117,954 (\$37.30/vol) with an associated total sediment amount of 146.77 tons. Therefore, when the sediment restriction value was reduced from 180 to 150 tons, (approximately 17 %) the minimum total cost increased by \$8,759 (around 8 %).



Variable cost	:	81,405	(\$25.75/vol)	Variable cost	:	95,424	(\$30.18/vol)
Fixed cost	:	27,790	(\$ 8.79/vol)	Fixed cost	:	22,530	(\$ 7.13/vol)
Total cost	:	109,195	(\$34.54/vol)	Total cost	:	117,954	(\$37.30/vol)
Total sediment	:	179.69	tons	Total sediment	:	146.77	tons

Figure 3.Results from ACO-FTPP for *Case I* (a) considering a sediment restriction of 180 tons, and *Case II* (b) considering a sediment restriction of 150 tons.

4. CONCLUSIONS

A specialized algorithm, ACO-FTPP, was developed for solving forest transportation planning problems with fixed and variable costs considering side constraints. The ability to consider these constraints allows us to address various environmental issues in road system management decision making.

ACO-FTPP was able to find a solution for both cases considered. We believe our approach is promising for solving large real forest transportation problems with multiple goals. ACO-FTPP can be easily modified to solve more complex transportation problems that consider multiple periods, products, origins and destinations. ACO-FTPP can also solve the problem of mills having a maximum volume capacity by including these mill capacities into the ACO-FTPP formulation as additional constraints.

Because ACO-FTPP is a heuristic algorithm, the solutions may not be optimal. Therefore, to test the performance of ACO-FTPP comparisons with exact techniques such a mixed-integer programming will need to be done. Additionally, since the algorithm parameters are heavily dependent on the nature and size of the problem, further evaluation of the robustness of the parameters should be done by applying ACO-FTPP to different problem types and sizes.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

An evaluation of forest road network by α- and β-indices*

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Abstract
The development of formation of forest road network over time can be expressed by α- and β-indices. The α- and the β-indices have been proposed to evaluate the degree of development of circular road networks. The indices are calculated easily from the number of nodes and the number of routes. The development of the forest road network of the University Forest in Hokkaido, the University of Tokyo, can be discussed by these indices. The Tokyo University Forest in Hokkaido has natural forest management, with mixed forest of cool- temperate broad-leaved species and sub-boreal conifers. The main research objective is to practice sustainable forestry management compatible with conservation of environment, keeping in line with natural diversity and ecosystem. The forest management was developed at almost the same time as the construction of forest road network. The road density in the forest has reached 41 m/ha since 1955. By the presence of a forest road network at a high density for natural forest management, even standing trees at a low price in the selection cutting stand can be sold. The results show that the circular road networks increase when $\alpha >= 0$ or $\beta >=1$. The relationship between α- and β-indices is simple and practical, and can ascertain the functioning of development change of the forest road network.

Keywords: α-index, β-index, forest road network, sustainable forest management, selection cutting

1. INTRODUCTION

There is a strong relationship between an α-index and a β-index, and they are related to the forest-road density and the degree of road nodal interconnection (Sakai and Naya, 1992). The developmental formation of a forest road network can be expressed by these indices. The University Forest in Hokkaido, the University of Tokyo, has an advanced extensive forest road network. The value of development of the forest road network is discussed with indices.

2. FOREST ROAD NETWROK OF THE UNIVERSITY FOREST IN HOKKAIDO, THE UNIVERSITY OF TOKYO

The natural forest management of the University Forest in Hokkaido shows a successful and good example of natural forest management. The main research objective of the University Forest management is sustainable harvesting compatible with conservation of environment, and keeping stable natural diversity and ecosystem. The high density forest road network has led to

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 193-197.*

successful implementation of management. The forest road network is well developed and functioned, and new construction has now decreased.

The University Forest in Hokkaido is situated in the central part of Hokkaido, 43°N, 142°E. The area covers 22,800 ha, altitude ranges from 200 m to 1,460 m, and the management area is 19,800ha.

The forest is located in the mixed forest zone between the cool- temperate zone with broad-leaved species and the sub-boreal zone with conifers such as *Abies, Picea, Taxus, Quercus, Betula, Fraxinus, Tilia, Acer, Salix* and other trees.

The University Forest was established in 1899, and the first forest management research plan was made in 1907. About 40 tree species are treated as valuable for management. Nowadays the average stand with selection cutting system has 800 trees of which 20 species DBH > 5 cm in a 250 cubic meters stand. The percentage of conifer trees is about 55 % in volume.

The method of natural forest management of the University Forest in Hokkaido is based on stand characteristics. Forest is classified into three types of stand, "selection cutting stand", "clear cutting stand", and "supplemental planting stand". The classification depends on whether natural regeneration is possible or not, and whether quality of the standing trees is high or not. For selection cutting, cutting intensity is usually 16 or 17 percent of standing volume on a cyclical basis every 10 or 20 years, respectively. For supplemental planting, natural regeneration is difficult to establish, and remaining trees are good in condition, therefore group selection cutting and planting are practiced. For clear cutting stand, natural regeneration is not possible, and trees have bad quality. After clear cutting, plantation is practiced. Planting species are almost always conifers growing in the University Forest nursery, whose parents are from the University Forest.

In 1950, felling and bucking were exclusively practiced by manual handling saw, pre-hauling by man and horse especially in winter, stacking by men, and transportation by forest railways extending 80km in the forest. From 1955 forest railways were converted to forest roads, and extended to 930km in 2004, with density at 41 m/ha. The forest management has coincided with the construction of forest road network. All forest roads have truck transportation capacity. The typical operation system is felling by chainsaw, pre-hauling by small tractors and truck transportation now. Forest road network is important to be extensive for intensive forest management. Since the forest road network has a high density in a natural forest management, even standing trees at a low price can be sold with competitive pricing (Miyamoto and Igarashi, 2004). The roads also contribute a considerable conservation value for water (Sakai et al, 2003) and biodiversity (Miyamoto and Igarashi, 2004).

3. α- AND β-INDICES

An α-index has been proposed to evaluate the degree of developmental formation of circular road networks (Ono et al, 1991). It is calculated from the following formula:

$$\alpha = (m - n + p) / (2n - 5), \qquad (1)$$

where n is the number of nodes, m is the number of routes, and p is the component of the network. The value p is 2 when the network is composed of two parts, and p is 1 for no separated parts. The numerator is a number of circular road networks (ν), wherein the denominator is a number of circular road networks when all nodes are connected to each other by a route. The α-index exceeds zero when circular road networks begin to be formed, and it approaches 0.25 as circular road networks are completed in the case of forest road network (Ono et al, 1991; Sakai and Naya, 1992).

On the contrary, the following β-index was previously used (Yeates, 1968).

$$\beta = m/n \qquad (2)$$

The β-index equals 1.0 when a simple connecting graph, and it approaches 1.5 as a network greatly interconnected (Yeates, 1968). The α- and β-indices are calculated easily by the number of nodes and routes.

From Equations (1) and (2), p = 1, and 1>>1/n,

$$\alpha = (\beta - 1 + p/n) / (2 - 5/n)$$

$$\approx (\beta - 1) / 2 \qquad (3)$$

This relationship can be derived in another way from a point of convergence, that is, α = 0.25, β =1.5, and the values when the minimum circular road network is formed, that is, α = 0, and β = 1.0. The α- and β-indices have a strong linear relationship with Equation (3) (Sakai and Naya, 1992).

4. RESULTS AND DISCUSSION

Forest road network in the University Forest in Hokkaido is shown in Figure 1.

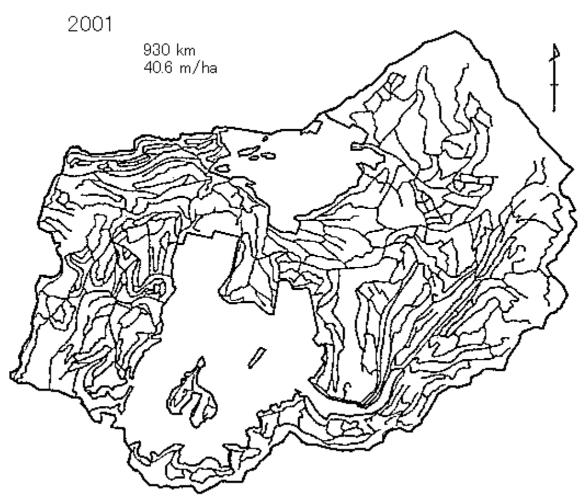

Figure 1. Forest road network in the University Forest in Hokkaido, the University of Tokyo.

Measured α- and β-indices and the number of circular roads (ν) are shown in Table 1. A forest road map of 1 to 50,000 is used for calculating the indices. During 1976 and 1986 there were no construction of circular roads, and new roads were only constructed as one-way road. This lack of circular construction is the reason for α and β decrease during 1976 and 1986. As anticipated by the characteristics of the β-index, circular roads increase when β >= 1. This increase in circular road formation also applies to the α-index when α >= 0.

It is reported that circular roads are increasingly formed when the road density exceeds 12 m/ha (Sakai and Naya, 1992). During 1966 and 1976, road density increased after the introduction of mechanized road construction system, whereby α-index exceeded 0. The result therefore suggests that it is necessary for the road density to exceed 12 m/ha at least in order to $\alpha >= 0$ or $\beta >= 1$.

Stage of the road development is shown in Figure 2. Taking into consideration that the forest road network in the University Forest in Hokkaido is well developed and functional in natural forest management, the value of $\alpha = 0.15$ should be the index or aim of forest road location and planning.

Table 1. The change of α- and β-indices, and circular road network of ν.

	1936		1956	1966	1976	1986	1993	2003
α	0	0	0	0.121	0.108	0.146	0.147	
β	0.947	0.5	0.794	1.215	1.194	1.277	1.282	
ν	0	0	0	102	98	164	218	
Density (m/ha)		4.0	1.0	3.5	25.9	30.2	37.3	41.0

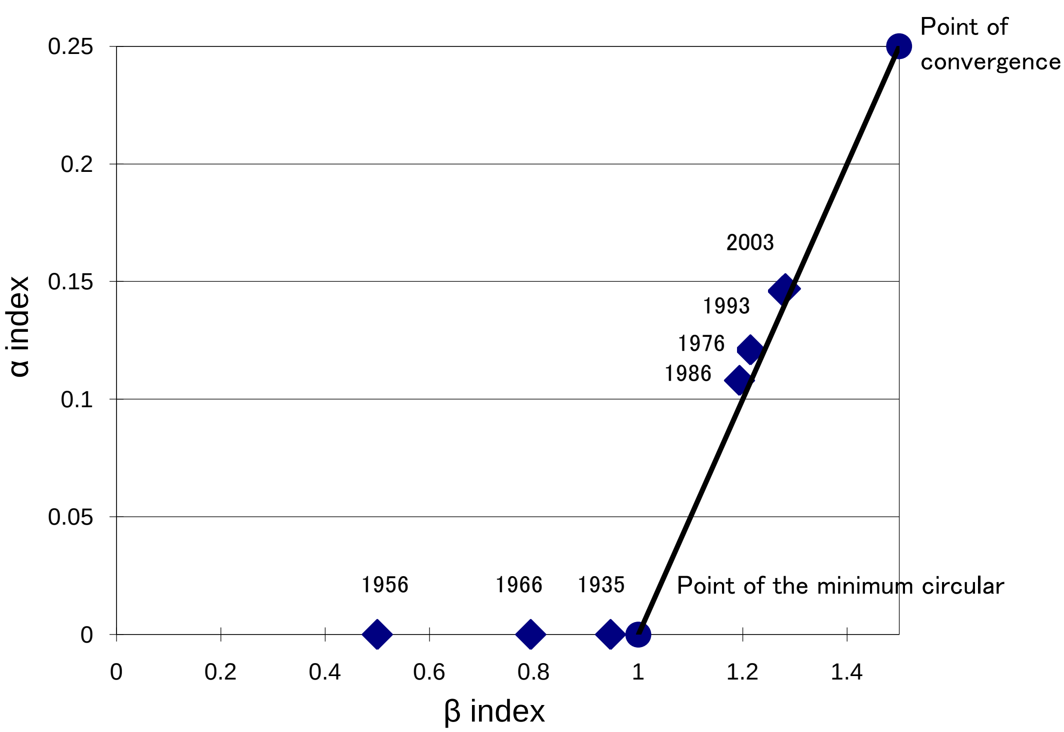

Figure 2. Relationships between α- and β-indices.

5. CONCLUSION

The relationship of Equation (3) is very simple and practical, and it is useful in converting both indices to each other. From Figure 2, the stage of development of circular road network can be assessed.

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Improving Timber Trucking Performance by Reducing Variability of Log Truck Weights*

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Abstract
We evaluated weight data from 79,760 truckloads delivered to 24 southern forest products mills in fall 2005 to assess opportunities for improving trucking efficiency by reducing the variability of gross, tare, and net weights. We compared the mean gross vehicle weight (GVW) at each mill to the federal weight limit of 40 tons and to any stated mill overweight policy. A benchmark group of suppliers was identified at each mill by selecting the five with the lowest coefficient of variation (CV) on their gross vehicle weights (GVW) to compare to the other suppliers at each mill. All mills had mean GVW significantly different from the federal limit of 40 tons at the 90% confidence level or stronger. A strong majority of loads delivered to each mill (77-100%) complied with the mill GVW policy. At most mills, the benchmark group had lower GVW variability as well as higher mean GVW and mean net weights. We observed that decreased GVW variability led to higher payloads—a 1% decrease in GVW variability yielded a 0.22 to 0.73 ton increase in payload weight. At 8 mills we observed that reducing the variability of tare weights helped reduce the variability of GVW—each 1% reduction in the CV of tare weight correlated to a 0.22-0.72% reduction in the CV of GVW. Only five mills showed any relationship between tare weight and payload variability. However, mean tare weight and mean net weight demonstrated an approximate 1:1 relationship at 15 mills. The BM groups at 14 of the 24 mills had significantly larger payloads and we project had 4 to 14% lower per ton hauling costs than other suppliers at the mills. Operating at the reduced variability level of the benchmark groups across the 221 million tons of roundwood annually consumed in the U.S. South suggests that $100 million of savings are potentially available.

1. INTRODUCTION

Transportation is not only the most public aspect of log extraction from the woods, but it is also the most expensive—and often limiting—step for the logging contractor. This project focused on the potential efficiency gains of fully loading trucks more consistently. Legal and corporate mill restrictions confine the weights that raw material transporters can haul. Hauling the maximum legal load every trip is the most cost efficient method of transporting raw materials.

2. LITERATURE REVIEW

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 199-208.*

Previous studies have examined the relationship between haul truck weights and productivity. Beardsell (1986) determined that there could be a substantial net gain in average payload by eliminating both overloading and underloading. He estimated the potential savings to two mills, using an approximate haul rate of $2.30 per loaded mile, as if all haul trucks arrived at the maximum legal gross vehicle weight (GVW) and no tare weights exceeded 27,000 pounds. The gross annual savings were $153,000 for the first mill and $431,000 for the second mill. Stuart (1995) also estimated the advantage of hauling fully loaded log trucks. If trucks average 77,500 pounds GVW, and the operation averages 15 loads per day assuming 175 days worked per year, the operation could increase its productivity 5% without making any changes in workers or machines. Assuming a $12 per ton cut and haul rate, hauling fully loaded would give a margin increase of approximately $27,000 per year in profit. A $16 per ton cut and haul rate would give a margin increase of approximately $37,500 per year.

Several studies have evaluated the benefits of in-woods weighing. McNeel (1990) evaluated the effect of modified tractor and trailer log truck weights on truck loads. On average the mean net load weight increased by 2.07 tons when on-board electronic scales were used. Gallagher *et al.* (2004) analyzed the difference in GVW between trucks that use scales and trucks that do not use scales (either in-woods platform scales or electronic on-board scales). In general, they found that trucks weighed in the woods had higher net payloads than those that were not weighed. In addition, trucks that utilized scales had higher average GVW than those without scales, and they had reduced variation of GVW. Shaffer *et al.* (1987) examined the use of on-board log truck scales using case studies of a Georgia logger and a Virginia logger. The use of scales by the Georgia logger decreased the standard deviation of net payload by 0.52 tons and decreased overweight fines but had no effect on mean net payload weight. The projected cost savings yielded an internal rate of return of 24.3% on the scale investment for the Georgia logger. The Virginia study found the scales were 98-99% accurate when compared to mill weights.

Mill policies also affect truck weights. Rayonier adopted a new truck weight policy at Georgia mills in January 2002 to discourage excessive truck overloading. As a result of the policy, the percentage of trucks with a GVW in excess of 44 tons decreased (Conradie *et al.* 2004). The percentage of underloaded trucks also decreased while the percentage of loads within 10% of the legal limit increased. The average GVW increased, as did the average payload. These increases in average values were the result of decreased variability of truck weights as demonstrated by the reduced coefficient of variation (CV).

Deckard *et al.* (2001) measured roundwood delivery turn times in the southeastern United States and estimated potential efficiency gains. They gathered data for 9,476 loads delivered to eight mills in the Southeast and separated the top 25% mills with the shortest median turn times and named this sample subset the benchmark group. They determined that if the remaining 75% of the sample mills (ROS=rest of sample) reduced their median turn times to those of the benchmark group, it would save $12.39 per load in direct marginal system costs. They placed the potential impact on the southern US wood supply chain at between $44.1 million and $87.1 million in 2001.

Beardsell (1986) determined two ways to buffer the problem of GVW variability: using scalehouse data and using weighing devices. The first method involves the mill setting a target GVW range, and sending reports on a systematic basis to suppliers indicating their performance relative to the performance of other mill suppliers. Overboe *et al.* (1988) discovered that providing load weight information to loader operators led to slightly decreased weight variability and greater profits.

Our study also examined variability of gross, tare, and net weights to determine if more uniform weights were associated with higher payloads and lower costs. We looked at GVW variability through comparisons of load frequency distributions and the performance of benchmark suppliers compared to the other suppliers to a mill. Relationships involving gross, tare, and net weights were also tested.

3. METHODS

To analyze haul truck weights, we gathered data from forest products mills across the Southeast operated by forest products companies that are members of the Wood Supply Research Institute (WSRI). The data consisted of haul truck weight information for all trucks delivering raw forest products (roundwood or chips) during four consecutive weeks. Specifically the data included date, truck weight in, truck weight out, contractor/supplier code, species and product code, state where the mill is located, and general information about any overweight policy of the mill. Trucks with tare weights less than 12 tons were removed from the data to exclude the small percentage of loads delivered by short-bed trucks or other non-traditional hauling vehicles. In addition, suppliers that delivered fewer than 10 loads in the four-week period were removed to assure that the suppliers in the analysis were suppliers that regularly delivered wood to each mill. Mills were grouped into two categories—saw/ply mills and pulp/OSB mills—based on the products delivered at each mill. The data analysis consisted of two parts:

- evaluating the means and variability of current gross vehicle, tare, and payload weights of trucks hauling to forest product mills across the southeastern United States, and
- estimating the potential cost savings associated with increasing gross vehicle or payload weights, and/or reducing the variability of the above measures.

One way to increase the efficiency of the wood supply system is to fully load trucks to the legal limit. To measure this we determined the average GVW of trucks hauling to a mill and compared it to the federal weight limit of 40 tons. We also examined frequency distributions of loads delivered to each mill to determine compliance with any mill overweight policies.

Without making structural or equipment changes to the current system, the potential performance of the system is reflected by the abilities of its top performers. We used methods for this data analysis that were similar to the methods used by Deckard *et al.* (2004) to compare turn times. The five suppliers at each mill with the lowest coefficient of variation of gross weight served as a benchmark (BM) group, and the remaining suppliers comprised the rest of sample (RS) group. We then determined if the mean GVW of the BM group was significantly different from the mean GVW of the RS group. Another way to potentially increase efficiency is to reduce variability of GVW, which should also help increase the number of fully loaded haul trucks. We compared the CV of GVW for the BM group to the CV of GVW for the RS group.

A second question examined the effect of GVW variability on net weight. We hypothesized that suppliers with more uniform GVW showed more control of how they load their trucks. We examined the statistical correlation of the CV of GVW with mean net weight, viewed plots of these values, and attempted to regress mean net weight with the CV of GVW where correlations and plots suggested that a relationship existed.

A third question investigated the effect of tare weight on payload. The first test determined if a more uniform truck fleet was related to a more uniform gross vehicle weight by examining the relationship between CV of tare weight and CV of GVW with regression. A second test to determine the effect of tare weight on payload strived to answer the question: do suppliers with smaller tare weights have higher control of net payloads? Regression analysis was used to test this hypothesis by evaluating the relationship between mean tare weight and CV of mean payload. A third test to examine the effect of tare weight on payload directly evaluated the relationship between tare weight and net payload. Because the two contributors to gross vehicle weight are tare weight and net payload, theoretically lower tare weights should correspond to higher net payloads. Again to test this hypothesis, we used regression analysis.

The second part of the study examined the potential cost savings if the suppliers to a mill had the same average payloads as the top suppliers. To quantify the savings, we compared the mean payload of the benchmark group to the mean payload of the rest of sample group at each mill. Next, we calculated haul cost per ton for the BM and RS groups at each mill using cost information from Mendell *et al.* (2006). Using their daily cost of $550 to own and operate a haul truck, a 50 mile one-way haul, and production of 3 loads a day with a 25.5 ton payload, the cost per ton-mile becomes $0.14, which is comparable to present haul costs (Gallagher *et al.*, 2004).

Lastly, we calculated the estimated savings for the South if all suppliers produced at the level of the average BM group. We assumed that 5% of loggers are currently managing for variability. We used U.S. Forest Service measurements of the volume of roundwood products harvested in the United States in 2001 to estimate the annual tonnage hauled in the South (Smith *et al.*, 2002). We assumed that all of the roundwood harvested was delivered by truck, and calculated the average per ton savings value for decreasing variability. This value was multiplied by the tons hauled per year in the South and multiplied by the percentage of loggers assumed to not currently manage variability to estimate the annual savings.

4. RESULTS AND DISCUSSION

The mills included 13 pulp/OSB mills and 11 saw/ply mills (Table 1). Products were both pine and hardwood. Loads received during the 4 week period at each mill ranged from 791 to 8,111, with a total of 79,760 in the sample. Tons purchased ranged from 21,376 to 207,742, with a total of 2,105,441 in the sample.

Mills were ranked based on CV of GVW. The lowest CV pulp/OSB mill had a CV of GVW of 4.10% while the highest CV pulp/OSB mill had a CV of GVW of 7.77%. The lowest CV saw/ply mill had a CV of GVW of 2.90% while the highest CV saw/ply mill had a CV of GVW of 6.62%.

All of the mills analyzed had mean GVW that were significantly different from the federal limit of 40 tons at the 90% confidence level. All mills except two pulp/OSB mills had mean GVW that were higher than 40 tons. A majority of the loads delivered to each mill complied with the mill policy; the percentages ranged from 77% to 100%. The BM group had a significantly higher mean GVW than the RS group at 16 of the 24 mills (Table 2). The BM group for all 24 mills had significantly lower CV than the RS group.

The BM group of 14 of the 24 mills had significantly larger payloads than the RS group. Assuming a haul cost of $550 per day and a production of 3 loads per day, the BM groups at each mill had 4 to 14% lower per ton hauling costs than the RS group.

Table 1. Gross weight, tare weight, and net weight statistics for the mills analyzed.

						Gross wt			*Tare wt*		*Net wt*					
	Mill	**State**	**Contractors**	**Loads**	**Tons**	**Mean**	**CV**	**p-value**	**Mean**	**CV**	**Mean**	**CV**	**Overweight Policy (OP)**	**≤ 40 tons**	**> 40 tons & ≤ OP**	**> OP**
				n		**tons**	**%**		**tons**	**%**	**tons**	**%**	**tons**		**% of loads**	
Pulp/OSB Mills	A	OK	50	5159	139,428	41.45	4.10	<0.01	14.43	7.05	27.03	7.02	42.5	17	73	10
	B	TX	100	3926	107,960	42.06	4.80	<0.01	14.56	7.21	27.50	7.59	N/A	19	N/A	81
	C	GA	25	5240	137,395	40.34	5.64	<0.01	14.12	4.6	26.22	8.95	44	49	48	3
	D	VA	62	5165	130,027	40.35	5.82	<0.01	15.18	7.05	25.17	10.15	46	49	51	0
	E	GA	100	8111	207,742	40.41	6.14	<0.01	14.80	5.34	25.61	9.53	N/A	49	N/A	51
	F	SC	29	5187	136,882	40.97	6.28	<0.01	14.58	8.46	26.39	9.80	N/A	39	N/A	61
	G	AL	30	5591	149,119	41.77	6.60	<0.01	15.10	6.27	26.67	11.12	44	29	58	12
	H	GA	35	1923	49,401	40.12	6.69	0.089	14.43	4.53	25.69	10.14	44	56	39	5
	I	AL	26	3333	89,057	41.93	6.71	<0.01	15.21	6.74	26.72	10.54	44	27	59	13
	J	AL	31	2345	61,215	40.97	6.93	<0.01	14.86	4.40	26.10	10.40	44	41	51	9
	K	VA	33	1515	36,892	39.66	7.34	<0.01	15.31	7.61	24.35	12.84	46	57	43	0
	L	VA	43	5284	128,389	39.26	7.42	<0.01	14.97	4.11	24.30	11.91	46	65	35	0
	M	TX	30	2359	61,953	40.83	7.77	<0.01	14.57	11.33	26.26	13.70	45	45	50	5
Saw/Ply Mills	N	OK	16	1386	38,725	41.86	2.90	<0.01	13.92	8.73	27.94	6.04	42.5	7	80	14
	O	NC	27	4082	106,393	40.50	3.13	<0.01	14.43	5.49	26.06	5.49	42	43	55	2
	P	AR	16	1962	54,515	41.94	3.44	<0.01	14.16	7.90	27.79	6.56	42.5	11	66	23
	Q	MS	19	2497	66,570	41.49	3.51	<0.01	14.83	6.34	26.66	6.19	42	14	75	11
	R	AR	40	3511	98,075	41.79	3.63	<0.01	13.85	6.74	27.93	6.48	42.5	14	66	20
	S	TX	27	2003	57,640	42.60	4.09	<0.01	13.82	6.83	28.78	6.95	N/A	12	N/A	88
	T	AL	27	2994	84,706	43.28	4.23	<0.01	14.96	7.06	28.29	7.39	44	7	77	16
	U	GA	14	796	21,376	41.68	5.77	<0.01	14.83	4.55	26.85	8.90	N/A	28	N/A	72
	V	GA	53	1787	47,801	41.41	6.17	<0.01	14.66	5.05	26.75	9.37	N/A	35	N/A	65
	W	AL	21	791	21,421	42.13	6.49	<0.01	15.05	7.31	27.08	10.75	44	23	63	14
	X	SC	30	2813	72,759	40.52	6.62	<0.01	14.66	4.99	25.87	10.48	N/A	47	N/A	53
			Totals	**79,760**	**2,105,441**											

Table 2. Comparison of benchmark and rest of sample groups' gross vehicle weights, coefficient of variations of gross vehicle weights, mean payload weights, and hauling cost per ton assuming production of 3 loads per day.

	GVW tons			CV of GVW %			Mean Payload tons			Hauling Cost $/ton			
Mill	**BM**	**RS**	**Difference**	**BM**	**RS**	**Difference**	**BM**	**RS**	**Difference**	**BM**	**RS**	**Difference**	**% Change**
Pulp/OSB													
A	42.30	41.26	1.04**	0.50	3.93	3.43**	28.01	27.05	0.96*	$6.55	$6.78	$0.23*	3.55%
B	42.85	41.67	1.18*	2.25	4.40	2.15**	28.35	27.29	1.06**	$6.47	$6.72	$0.25**	3.87%
C	41.25	40.07	1.18**	2.73	5.51	2.78**	27.08	26.07	1.02*	$6.77	$7.03	$0.26*	3.91%
D	42.87	40.03	2.84**	2.00	5.14	3.14**	27.94	24.86	3.08**	$6.56	$7.38	$0.81**	12.39%
E	41.28	40.35	0.94	2.24	5.08	2.84**	26.49	25.60	0.89	$6.92	$7.16	$0.24	3.47%
F	41.77	39.54	2.23**	1.95	5.75	3.80**	27.66	24.37	3.29**	$6.63	$7.52	$0.89**	13.49%
G	43.26	41.37	1.90**	2.13	6.00	3.88**	27.98	26.14	1.83**	$6.55	$7.01	$0.46**	7.01%
H	40.42	40.04	0.38	4.07	6.44	2.37**	25.93	25.64	0.29	$7.07	$7.15	$0.08	1.14%
I	42.74	41.41	1.33**	4.19	6.71	2.52**	27.44	26.28	1.16**	$6.68	$6.98	$0.29**	4.41%
J	40.20	40.95	-0.74	3.10	6.35	3.25**	25.37	26.10	-0.72	$7.23	$7.03	-$0.20	-2.77%
K	41.42	38.87	2.55**	2.91	6.24	3.34**	26.52	23.26	3.26**	$6.91	$7.88	$0.97**	14.03%
L	40.46	38.85	1.61**	2.86	6.00	3.14**	25.74	23.98	1.76*	$7.12	$7.64	$0.52*	7.33%
M	41.70	40.37	1.34	4.37	7.20	2.83**	27.74	25.89	1.85**	$6.61	$7.08	$0.47**	7.15%
Saw/Ply													
N	42.10	41.72	0.38**	0.84	2.73	1.89**	28.27	27.99	0.28	$6.48	$6.55	$0.06	1.00%
O	40.92	39.90	1.02**	1.34	4.04	2.70**	26.24	25.45	0.79	$6.99	$7.20	$0.22	3.10%
P	42.23	41.01	1.22**	1.53	4.79	3.27**	28.14	26.57	1.57**	$6.52	$6.90	$0.38**	5.89%
Q	41.56	41.23	0.33	1.58	4.35	2.77**	26.93	26.34	0.58	$6.81	$6.96	$0.15	2.22%
R	42.26	41.53	0.73**	0.56	3.42	2.86**	28.84	27.76	1.08**	$6.36	$6.60	$0.25**	3.88%
S	43.27	42.07	1.20**	2.16	4.51	2.36**	27.40	27.74	-0.33	$6.69	$6.61	-$0.08	-1.20%
T	43.70	42.88	0.82*	1.76	4.51	2.75**	29.41	27.56	1.85**	$6.23	$6.65	$0.42**	6.71%
U	41.31	41.00	0.31	3.40	6.63	3.23**	26.58	26.19	0.38	$6.90	$7.00	$0.10	1.46%
V	40.26	41.39	-1.14	2.34	5.44	3.10**	26.07	26.74	-0.68	$7.03	$6.86	-$0.18	-2.54%
W	42.01	42.17	-0.16	3.48	7.27	3.80**	27.32	26.91	0.41	$6.71	$6.81	$0.10	1.52%
X	41.77	40.07	1.71**	3.70	6.73	3.02**	27.30	25.50	1.81**	$6.72	$7.19	$0.48**	7.08%

**Significant at alpha 0.05 *Significant at alpha 0.10

Approximately 221 million tons of roundwood were hauled in the U.S. South in 2001 (U.S. Forest Service, 2002). Using this tonnage, and assuming 5% of loggers already manage variability, the U.S. South wood supply chain could save approximately $100 million by reducing variation of payload.

Reducing GVW variability was associated with higher mean net payloads at 19 of 24 mills. We saw a significant inverse relationship between the CV of GVW and mean payload. A 1% decrease in GVW variability yielded a 0.22 to 0.73 ton increase in payload at individual mills. When the data from eleven significant pulp/OSB mills and data from the eight significant saw/ply mills was combined, the general trend remained the same (Figure 1). The sawtimber loads generally have higher payloads than pulpwood loads because sawtimber is a more consistent product that is easier to load to maximum GVW than pulpwood.

More uniform tare weights were associated with more uniform gross vehicle weights at 8 of 24 mills. We found no relationship at 16 of the 24 mills. A 1% reduction in variability of tare weight resulted in a 0.22 to 0.72% reduction in GVW variability at individual mills. When the data from the five significant pulp/OSB mills and the three significant saw/ply mills was combined, the relationship between CV of tare weight and CV of GVW was only significant for the pulp/OSB mills (Figure 2).

Lower tare weights were not correlated with more uniform payloads at 19 of the 24 mills. Five of the 24 mills showed a significant direct relationship between mean tare weight and payload variability. At these mills a 1 ton reduction in tare weight led to a 0.08 to 4% reduction in payload variability. Because only five mills had a significant relationship between tare weight and payload variability, the relationship between these two factors is difficult to quantify as payload variability is likely linked to several elements other than tare weight. Although the exact relationship is elusive, there is at least some benefit of lower variability as tare weight is reduced.

Higher payloads were associated with lower tare weights at 15 of the 24 mills. We saw a significant inverse relationship between mean tare weight and mean net weight at those mills. A 1 ton reduction in tare weight approximately correlated to a 1 ton increase in net payload (Figure 3). Lower tare weights are clearly correlated to higher payloads.

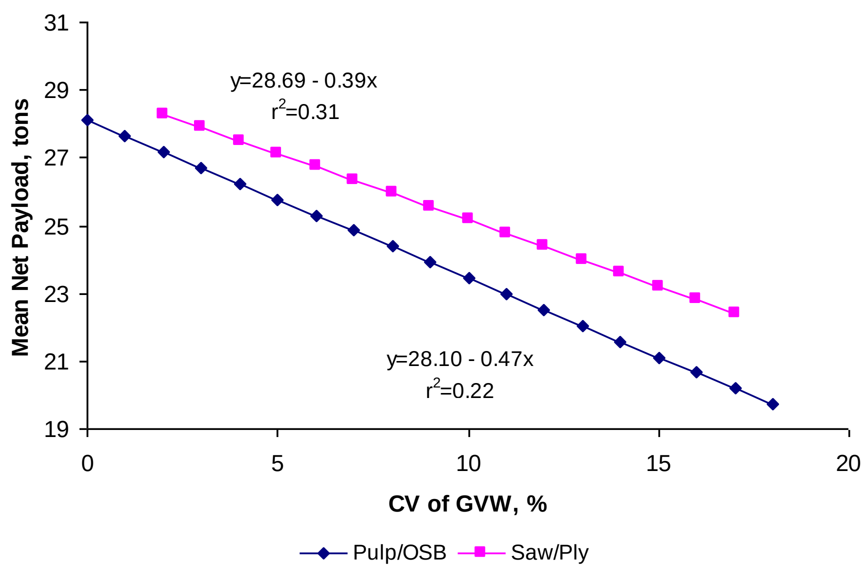

Figure 1. Relationship of CV of GVW to net payload.

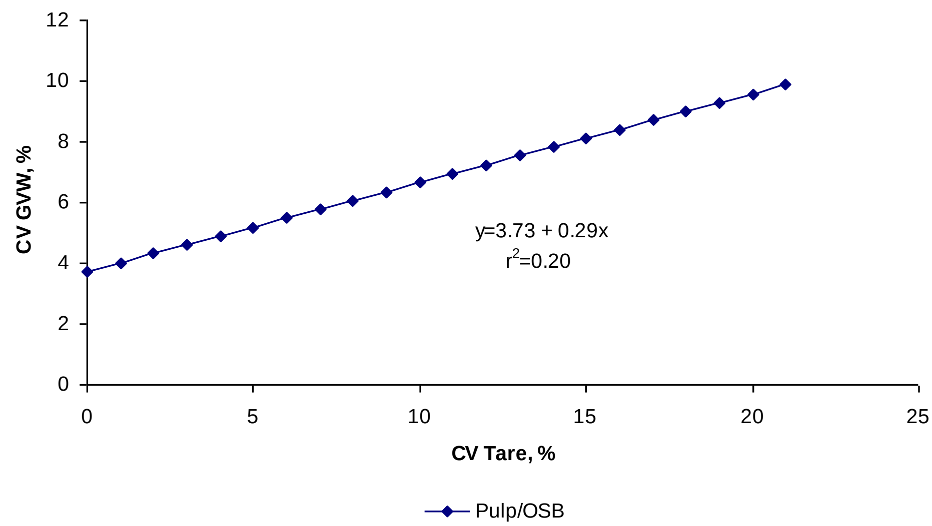

Figure. 2. Relationship of CV of tare weight to CV of GVW.

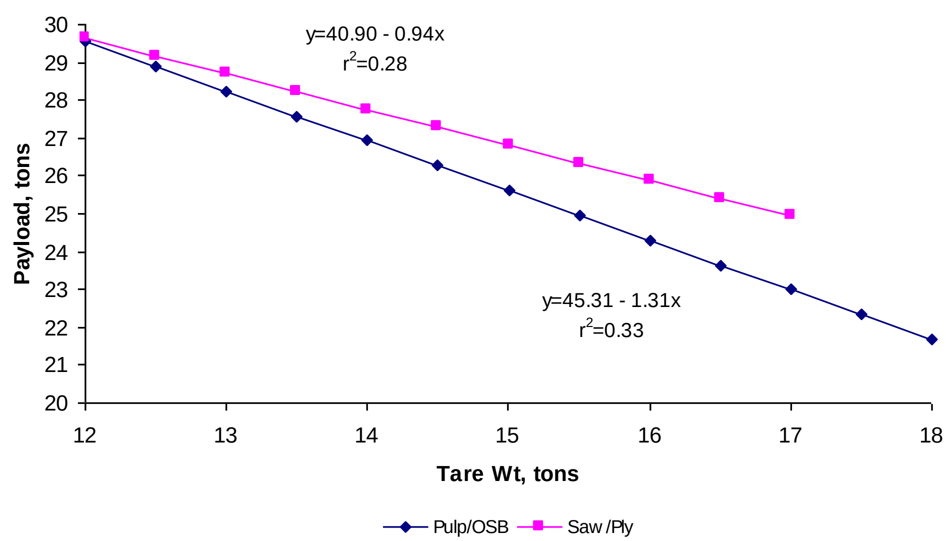

Figure 3. Relationship of tare weight to net weight.

5. CONCLUSIONS AND RECOMMENDATIONS

Our results show that (1) mills can control their gross vehicle weight distributions by enforcing overweight policies, (2) suppliers can achieve maximum hauling efficiency if they consistently haul fully loaded trucks, and (3) lighter weight trucks correspond to higher payloads.

On a mill-wide scale, mills can control their GVW distributions by enforcing overweight policies. Mill overweight policies did have an effect on average GVW. The percentages of loads in compliance with the mill policies ranged from 77% for Mill P (overweight policy of 42.5 tons) to 100% for Mills D, K, and L (overweight policy of 46 tons). Minimizing load variability will positively affect the entire wood supply system. Mills could set a target variability and GVW range for suppliers, similar to the target system proposed by Beardsell (1986). The target GVW range must be balanced between cost, risk, and liability. If the target range is less than the state limit, then lower payloads and higher cost will cause suppliers to lose money. If the target range is much greater than the state limit, liability and risk will increase as trucks will strive to run overloaded. Suppliers should strive to keep GVW within the target range to ensure maximum payloads, and should strive to maintain a CV within the variability range to ensure consistent payloads. The mills could provide regular progress reports to suppliers showing their variability and GVW in relation to other suppliers and the mill target.

Suppliers that regularly haul fully loaded trucks receive the maximum benefit. There was a group of suppliers at each mill with significantly less variable GVW. For 16 out of the 24 mills the least variable five contractors had a higher average GVW than the rest of the suppliers. Suppliers can increase GVW by hauling more uniform loads. One way suppliers can reduce their load variability is to use scales, on-board (electronic or air) or platform, to measure load weights.

The payloads of the least variable (most consistent) group of suppliers were higher than those of the rest of the suppliers. In the cost analyses, the BM group hauled more wood, at a lower cost, for more revenue than the RS group. For each mill the more uniform suppliers had 4% to 14% hauling cost savings compared to the rest of the suppliers. Reducing variability, through scales or other means, will yield higher revenues and cost savings. The United States southern wood supply chain could potentially save $100 million by reducing payload variability. This estimate of cost savings is conservative as suppliers were compared to the best local benchmark group instead of the best benchmark groups across the region.

There was an inverse relationship between the variability of GVW and mean net payload. The less variable GVW yielded higher net payloads. If suppliers can control their GVW, using whatever method, they can more effectively raise payloads.

We also found that lighter weight trucks contribute to higher payloads. The inverse relationship between average tare weight and average net weight observed at 15 mills supports this conclusion. Each 1 ton reduction in tare weight approximately resulted in a 1 ton increase in payload. Contractors should use lightweight tractor-trailer rigs to increase payloads, and therefore increase revenue. Lighter trucks can be purchased, or existing rigs can be modified to be more lightweight.

Lower tare weights can somewhat contribute to more uniform loads. The direct relationship between average tare weight and payload variability at five of the mills indicates that lower tare weights can contribute to reduced payload variability, although the exact relationship between the two is variable.

Managing uniform truck fleets by itself will only result in small gains in payload; load weights must be measured to further control variability. There was a direct relationship between tare weight variability and GVW variability at 8 of 24 observed mills. Less variable tare weights resulted in less variable GVW, although a 10% reduction in tare weight variability only yielded about a 2 to 7% gain in payload. Suppliers can control tare weight variability by maintaining uniform truck fleets. When purchasing new trucks, trucks should be purchased with similar—preferably lower—tare weights. This will aid in controlling GVW, which will in turn increase payloads.

This analysis did not separate loads or suppliers by product. The product hauled may have affected the variability of some of the suppliers. Accounting for this source of variability may also affect the projected savings. Additional analyses are underway to evaluate these issues.

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Development of a Forest Road Route Survey Method Compromising Zero-line Survey and Center-line Survey and Review of its Applicability*

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Abstract
In order to select forest road routes in steep mountainous areas, a survey method compromising center-line and zero-line surveys was developed. In order to examine its applicability, routes planned for three forest roads were selected to survey and design according to the conventional method and the compromise method. In addition, road alignment and work load of the selected forest road routes were compared between the conventional survey method and the compromise survey method by selecting 61 survey sections from already constructed forest roads. When a forest road route was selected based on the compromise method, the number of intersection points increased by 12 percent on average. However, the number of changes in road gradient was reduced by 36 percent on average. This indicates that improved road alignment can be maintained. As for road alignment and soil mass distribution, in the case of the conventional method, radius of curvature was over 15 meters only in 44% of total sections while a balance of cutting volume and banking volume was maintained only in 1/3 of total sections. However, in the case of the compromise method, radius of curvature was over 15 meters in the entire section and a balance of cutting volume and banking volume was maintained as well. In addition, site area was decreased by 37 percent, indicating that forest destruction caused by forest road construction can be mitigated. Cutting volume was reduced by 43% (rock cutting volume by 60%) and banking volume was decreased by 35% in the compromise method compared to the conventional method. In addition, earth volume for ditches and road slope areas (rock slope area) were reduced by 15% and 40% (68%), respectively. On the other hand, the length of slope stabilization structure has increased by 2.04 times.

1. INTRODUCTION

About two-thirds of the land in Korea is mountainous types, which features steep slopes in many sections. Forest roads in Korea may be divided into two grades: main forest roads and branch forest roads. As of the end of 2005, the density of forest roads was 2.5m/ha (Korea Forest Service (KFS), 2006).

The road alignment of a route is a three-dimensional form of a forest road shaped by the center-line of the road. Therefore, in order to decide on a reasonable road alignment, a three-dimensional road alignment should be created by combining cross-sectional, horizontal and longitudinal road alignments to carefully review the surrounding topography and road alignment elements before and after the road construction and fully consider the driving-dynamic conditions of vehicles as well as social demands for environment conservation. If surrounding

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 209-219.*

topography and road alignment elements are not fully considered, despite increased destruction areas and excessive construction cost, road alignment will be poor and the stability of road beds will be lowered, which may lead to disasters such as the collapse of roads.

For the selection of forest road routes, two methods are available: the center-line survey method and the zero-line survey method. The center-line survey method features a strong horizontal concept. Although it has an advantage of being able to define horizontal alignment on site, it is difficult to predict the generation and distribution of soil mass because longitudinal alignment is not defined. On the other hand, the zero-line survey method has a strong vertical concept. Its longitudinal alignment is defined on site and a balance of cutting volume and banking volume is maintained at every intersection point. However, horizontal alignment changes drastically, and soil mass distribution is difficult in steep slope areas.

In particular, in the case of forest roads in Korea, facilities are mostly located in mountainous areas where topographical changes are drastic and workload varies greatly depending on the road alignment of a route. Therefore, it is necessary to review three-dimensional road alignments combining cross-sectional, horizontal and longitudinal road alignments as well as soil mass distribution for the road to be appropriate to local topography.

However, when the conventional forest road route selection process is examined, a surveyor selects a route by first considering horizontal alignment based on his subjective and high-level judgment of topography. As a result, the selected routes often do not relate to topography.

Therefore, this study was conducted to develop an environmentally-friendly and economical forest road route selection method by 1) developing a compromise method that takes advantage of the center-line survey method and the zero-line survey method, 2) examining three-dimensional road alignment as well as soil mass distribution on site, and 3) analyzing its applicability.

2. MATERIALS AND METHODS

2.1 Developing a center-line and zero-line compromising survey method

In the conventional forest road survey & design approaches, a cross-sectional alignment is decided only after a center-line survey is performed on site, longitudinal alignment is set in the design process and the planned height of each center point is calculated.

At this time, if the cross-sectional alignment is not appropriate to local topographical conditions, change and modification of longitudinal lines and review of cross-sectional alignment need to be repeated until the cross-sectional alignment becomes appropriate. In a section where the ground gradient is steeper than a banking slope design gradient, banking is not possible in a natural state. For such steep areas, slope stabilization structures should be placed for banking, or a planned height should be changed by adjusting longitudinal alignment to be a cutting type.

As described, a banking slope design gradient is a very important factor in determining the adequacy of cross-sectional road alignment of forest routes. If slope gradient is gentle, the slope stability is enhanced. However, it also increases the work load and the construction cost. Therefore, it is critical to determine the appropriate banking slope gradient.

The current forest road banking slope gradient design requirement is 1:0.9±0.2 (KFS, 2000), which is steeper than the regular road requirement of 1:1.5~1.8 (Korea Highway

Corporation, 1992) or the foreign forest road design criteria of 1:1.3~1:1.5 (Roetzer, 1985; Japanese Forest Road Research Society, 1997).

If the banking slope gradient is changed to be gentler than the current design requirement, banking is not possible in some spots that were designed to be a half-bank & half-cutting cross-section judging that banking is possible according to the current design requirement that is spots where the ground gradient is steeper than the banking slope gradient. Therefore, it should be designed to create an appropriate cross-sectional road alignment by setting up slope stabilization structures on banking parts, lowering a planned height or vertically moving center points to the cutting area.

Setting up slope stabilization structures on banking areas may result in problems such as increased construction cost and disharmony with surrounding natural landscape. Therefore, it is recommended to avoid this option, if possible. Lowering a planned height may also result in unreasonable longitudinal alignment when planned height change volume is not consistent in every intersection point. In order to maintain a certain longitudinal gradient as well as stable cross-sectional alignment in every spot, spots with excessive cutting will be inevitable. Horizontally moving a center point toward a cutting area will enable to maintain a certain longitudinal gradient while creating appropriate cross-sectional alignment with no spots that produce excessive cutting as the center point is relocated. However, since it changes horizontal road alignment, it is difficult to apply in the conventional method.

Therefore, when setting a centerline on a site in order to create appropriate cross-sectional alignment throughout the entire route, while maintaining reasonable horizontal alignment and longitudinal alignment, the center-line & zero-line compromising survey method was developed to review local topography and three-dimensional alignment altogether.

2.2 Analyzing applicability of the compromise survey method

2.2.1 Actual survey and design of routes

At Gwangreung Laboratory Forest of Korea Forest Research Institute located across Pocheon county and Namyangju city in Gyeonggi province, planned routes (three routes, about 2.2km) were actually surveyed and designed in the conventional survey method and the compromise method. In order to compare road alignment and design performance of different survey methods under the same topographical conditions, the planned routes were selected within paths of the same route. The general overview of routes is described in Table 1.

Table 1. General description of forest road investigated

Factor		Total	Route Ⅰ	Route Ⅱ	Route Ⅲ
Length of road (m)		2,167.4	679.1	892.7	595.6
Proportion by slope of site (%)	< 30%	6.9	3.9	10.6	4.5
	31~55%	67.3	81.7	49.9	77.1
	56% <	25.8	14.4	39.5	18.4
Proportion of rock section (%)		64.6	55.2	52.7	93.4
Average soil depth of rock section (m)		0.53	0.47	0.69	0.44

2.2.2 Route design and applicability analysis

Planned routes for each survey method were designed by applying design criteria defined in KFS Forest Road Facility Regulations (KFS, 2000). However, among design criteria, 1:1.5 was applied for banking slope gradient in consideration of slope stability.

In addition, in order to verify applicability at 61 survey spots along already built forest roads, road alignment, work load and construction cost (on a basis of construction unit price) of each survey method were investigated and compared.

3. RESULTS AND DISCUSSION

3.1 Overview of compromising forest road route survey method

In order to set a center point appropriate to local topography, the compromising forest road route survey method was developed by adding zero-line survey before center-line survey as shown in Fig. 1.

As described in Fig. 1, the proceedings of the compromising forest road route survey method are as follows:

① After a field investigation, set a planned (longitudinal) gradient appropriate to local topography. Then, set a zero point (formation level, planned height) according to this planned gradient and conduct the zero-line survey.

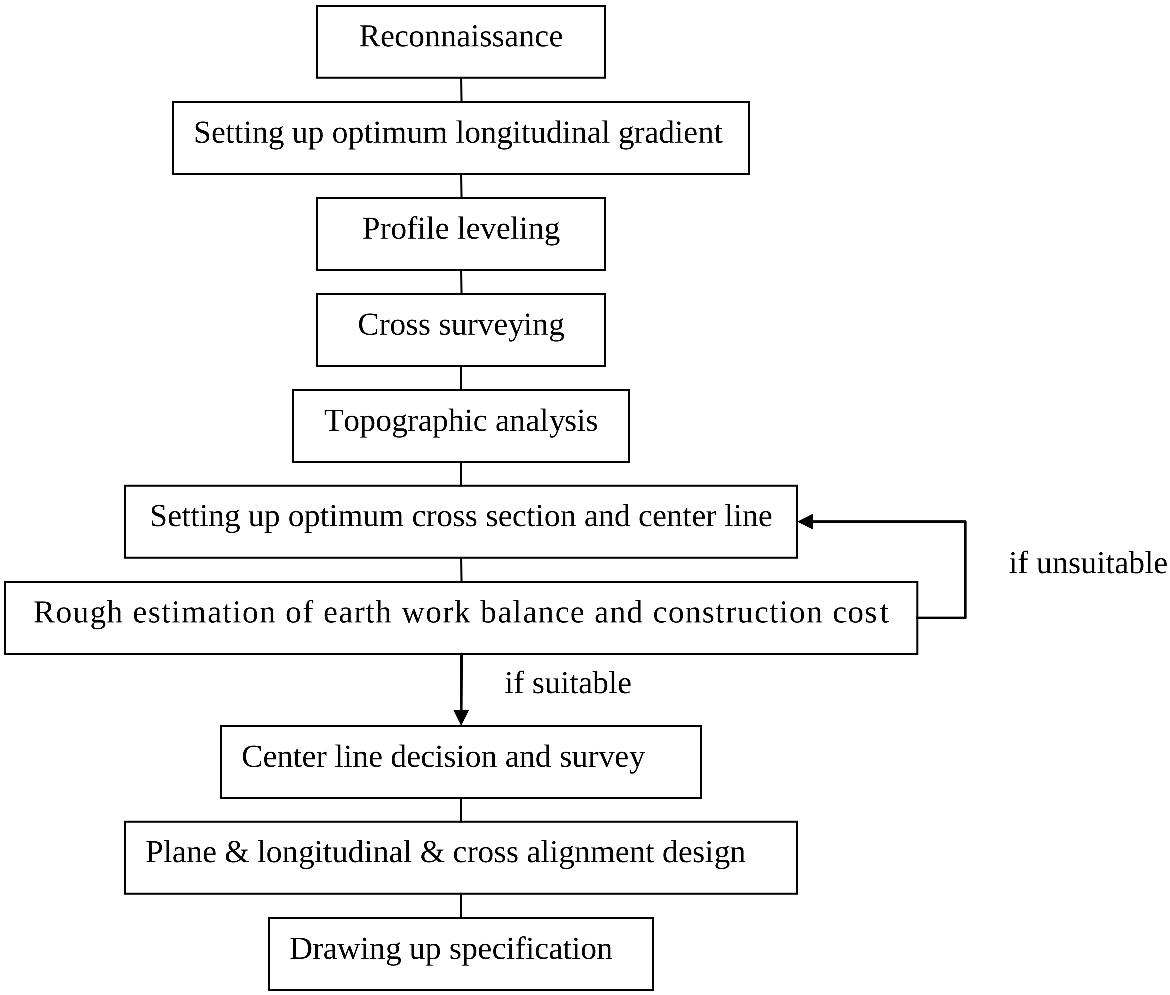

Figure. 1. Forest road design process of developed compromise method

② By considering stability after construction, soil mass distribution and forest road site width based on ground gradient from the zero point, set the intersection point (IP) on the basis of zero point to create appropriate cross-sectional road alignment and survey every IP. If curvature is necessary, set the range of bend radius appropriate to local conditions and record it in a field book. Then, determine the possibility of banking according to the ground gradient and set the IP by calculating a horizontal distance between the zero point and IP to create appropriate cross-sectional road alignment.

③ Based on survey results from Steps 1 and 2, define the cross-sectional specifications of each intersection point and calculate the high-level estimated earthwork. When the estimated earthwork needs to be adjusted, the IP should be horizontally moved. However, the adequacy of formation cross-section after adjustment needs to be examined.

④ Once a center point is decided, set the IP from beginning point (No. of IPs and +IP).

In the case of forest road routes set by this process, the soil mass from cutting areas in steep slopes (or ridge) is transported to banking areas in gentle slopes (or valleys) to improve soil mass distribution. Avoidance of excessive banking in steep slopes prevents forest road disasters and reduces the destruction of forest landscape. In addition, by separating cutting areas (ridges) and banking areas (valleys), forest road routes may be selected to cut in a 凸-shaped ridge in an upward crescent form and to transport and bank in a 凹-shaped valley in a downward crescent form. Then, in an area where forest landscape is destroyed, upward and downward crescents will alternate. Compared to the conventional method (forest landscape destruction sites are exposed in a belt type as the entire section of the route is cut and banked in the same width), it was judged to be more favorable in forest aesthetics as well.

3.2 Review of applicability of the compromising forest road route survey method

3.2.1 Comparison of forest road alignment of different survey methods

The number of IPs and horizontal and longitudinal road alignment of different survey methods were compared, which is shown in Fig. 2.

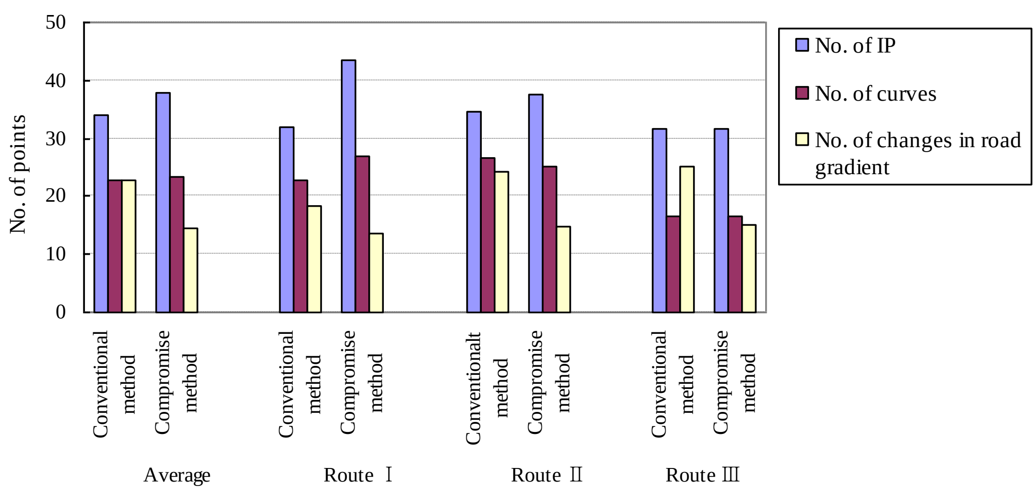

Figure 2. Road alignments by survey methods

Figure 2 shows that in the compromise method, the number of IPs is increased by about 12% (Route I: increased by 36%, Route II: increased by 9%, and Route III: same) compared to the conventional method. The number of curvature spots were increased by about 3% (Route I: increased by 18%, Route II: decreased by 5%, and Route III: same), while the number of changes in road gradient was reduced by about 36% (Route I: decreased by 36%, Route II: decreased by 39%, and Route III: decreased by 40%).

The above shows that the number of IPs increases somewhat in the compromise method compared to the conventional method, because all topographical change points are defined as IPs. However, favorable longitudinal road alignment seemed possible as forest road alignment is decided by fully considering local topographical conditions.

3.2.2 Road alignment structure

Forest road alignment is a three-dimensional shape of forest road centerlines. Since it plays a critical role for safe driving of vehicles and smooth traffic flow, efforts should be made to design forest roads with better road alignment.

At forest road turns, horizontal curves need to be set up to secure transportation safety and avoid a decline in driving speed and transport capacity. The radius of curvature should be long, if possible, for the safe driving of vehicles. In the Korean forest road facility regulations, minimum radius of curvature is set at 15~60 meters in regular topography and 12~40 meters in special topography depending on design speeds.

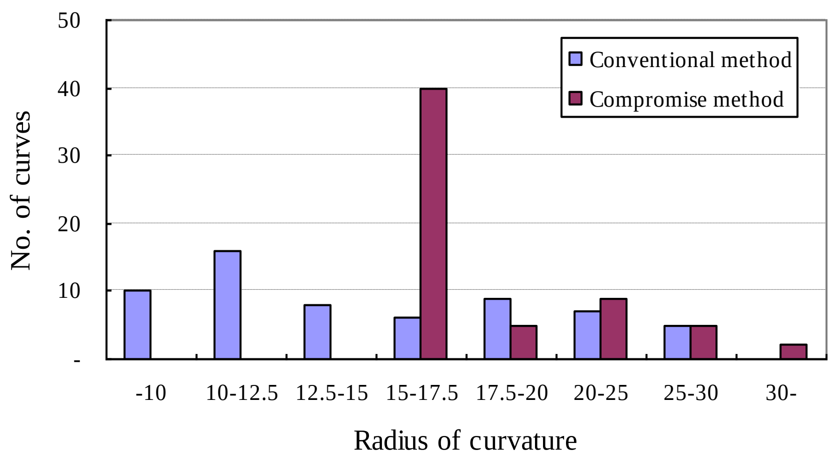

Figure 3. Radius of curvature by survey methods

According to the distribution of radius of curvature in the conventional method shown in Figure 3, out of 61 spots, 10 sites (16%) were less than 10 meters, 16 sites (26%) were 10~12.5 meters, 8 sites (13%) were 12.5~15 meters, 6 sites (10%) were 15~17.5 meters, 9 sites (15%) were 17.5~20 meters were, 7 sites (12%) were 20~25 meters, and 5 sites (8%) were 25~30 meters. In 56% of total spots, radius of curvature was less than 15 meters.

However, in the case of the compromise method, 15~17.5 meters were 40 sites (66%), 17.5~20 meters were 5 sites (8%), 20~25 meters were 9 sites (15%), 25~30 meters were 5 sites (8%) and over 30 meters were 2 sites (3%). Compared to the conventional method, radius of curvature was extended. In addition, forest road alignment structure can be improved so that radius of curvature will be over 15 meters in the entire section.

3.2.3 Soil mass distribution

When using cutting soil for banking within each section in order to minimize earth volume when building forest roads, it should be distributed to minimize transport distance. To this end, a balance of cutting volume and banking volume within a unit section connected by ridge-valley-ridge should be maintained.

At this time, cutting soil is in its natural state while banking soil is in hardened state. Therefore, soil conversion coefficient (C), a volume ratio between cutting soil and banking soil, should be calculated in order to understand the balance between cutting volume and banking volume. That is, when banking volume and cutting volume distribution ratio (banking volume/cutting volume) within a unit section is close to the soil conversion coefficient, soil mass balance is in a favorable state.

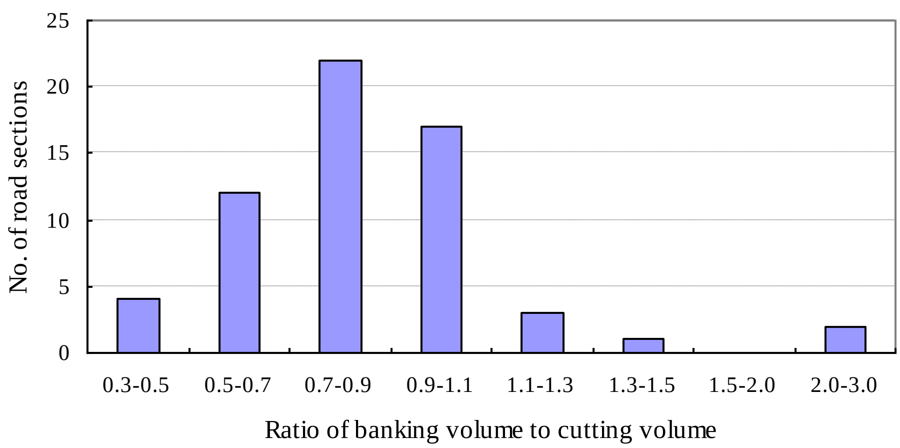

Figure 4. Ratio of banking volume to cutting volume in conventional method

Usually soil conversion coefficients are applied by setting standard values by soil types. In this study, 0.9~0.95 (sandy soil mixed with boulder) was applied as a standard value.

Figure 4 shows the distribution ratio of banking volume and cutting volume in the conventional method. Out of 61 spots, 4 sites (6%) were 0.3~0.5, 12 sites (20%) were 0.5~0.7, 22 sites (26%) were 0.7~0.9, 17 sites (28%) were 0.9~1.1, 3 sites (5%) were 1.1~1.3, 1 site (2%) was 1.3~1.5, and 2 sites (3%) were 2.0~3.0. This indicates that a balance of cutting volume and banking volume within a unit section was maintained in less than 1/3 of the total sections.

However, in the case of the compromise method, the distribution ratio of banking volume and cutting volume ranged in 0.92~0.94 in all survey spots, indicating that the entire volume of cutting soil generated can be used for banking soil within the same unit section and transport distance can be minimized.

3.2.4 Work load

1) Cutting volume and banking volume and digging side ditches

Earth volumes of different survey & design methods, including cutting volume, banking volume and side ditch digging, are compared and shown in Figure 5.

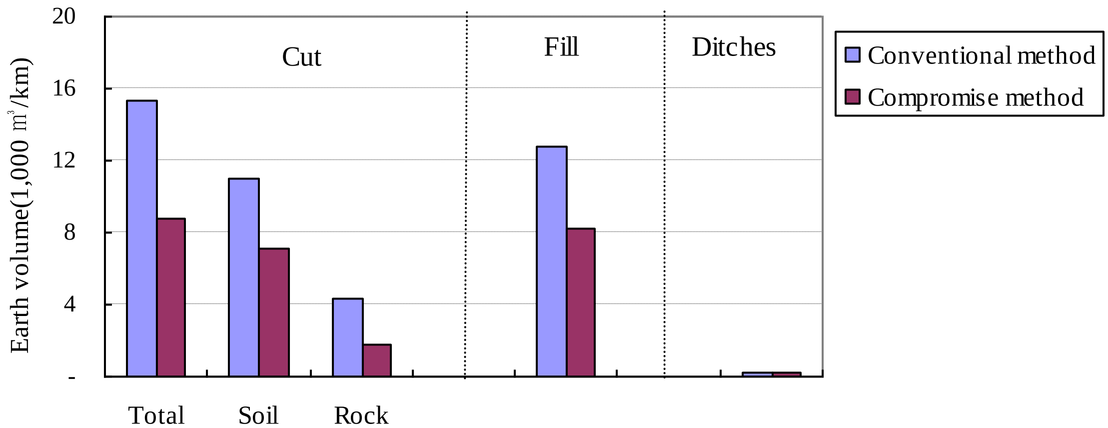

Figure 5. Earth work volume by survey methods

Figure 5 shows that in the conventional method, cutting volume was 15,370 m^3/km on average. However, in the compromise method, it was estimated to be reduced by 43% to 8,830 m^3/km in average.

By soil texture, soil cutting volume is estimated to be reduced by about 35% from 11.04 m^3/km to 7.09 m^3/km on average. In the case of rock cutting volume, which is relatively difficult in construction works and requires higher construction costs, it is estimated to decline by 60% from 4,330 m^3/km to 1,740 m^3/km on average when the compromise method is applied.

Banking volume is estimated to decrease by about 35% from 12,740 m^3/km to 8,220 m^3/km when the compromise method is applied. Earth volume of ditches is presumed to be reduced by 15% from 270 m^3/km (soil: 0.22 m^3/km, rock: 0.05 m^3/km) to 230 m^3/km (soil: 0.19 m^3/km, rock: 0.04 m^3/km)

2) Area of road prism

Figure 6 shows that a area of road prism requires 2.55ha/km (slope area: 2.94ha/km) in the conventional method. However, when the compromise method is applied, a forest road site area requires 1.62ha/km (slope area: 1.85ha/km). This indicates that the area can be reduced by 37% compared to the conventional method.

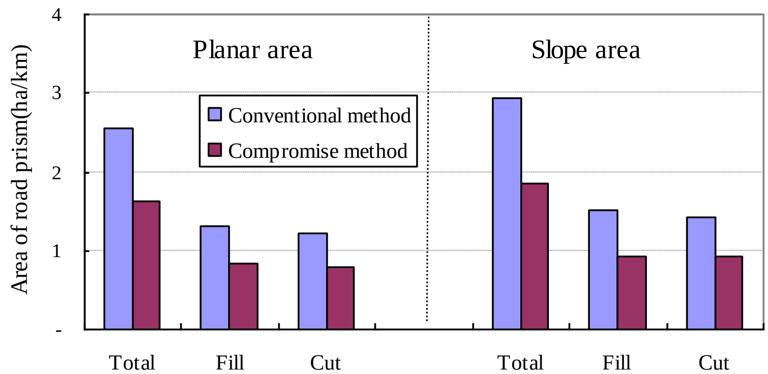

Figure 6. Area of road prism by survey methods

By structure parts, cutting area is estimated to decrease by about 37% from 1.32ha/km (slope area: 1.51ha/km) to 0.83ha/km (slope area: 0.93 ha/km) on average, while banking area is reduced by about 36% from 1.23ha/km (slope area: 1.43ha/km) to 0.79ha/km (slope area: 0.92 ha/km).

This indicates that when the compromise method is applied, forest roads can be also built in sites smaller than those used currently.

3) Forest road slope area

Forest road slope area is the area of cutting and banking slopes that newly become bare land. It serves as a basis for calculating the slope afforestation work load.

According to forest road slope areas of different survey and design methods shown in Figure 7, an average of 2.07ha/km of forest road slope area was generated when a forest road was newly opened using the conventional method. However, when the compromise method was applied, forest road slope area was 1.23ha/km on average, producing about 40% reduction compared to the conventional method.

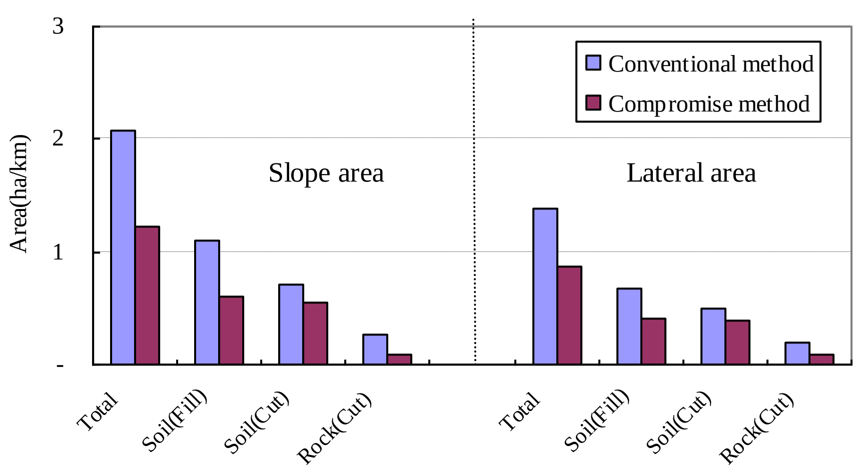

Figure 7. Area of cut and fill slopes by survey methods

By soil texture, soil slope area was reduced by about 36% from 1.81 ha/km to 1.15 ha/km on average. Meanwhile, rock slope area, which requires higher construction cost for afforestation compared to soil slopes and early afforestation is challenging, was reduced by about 68% from 0.26 ha/km to 0.08 ha/km on average.

When lateral areas of forest road slopes are compared across different survey & design methods, the lateral area was 1.38 ha/km on average due to the opening of a forest road using the conventional method. When the compromise method was applied, it was 0.87 ha/km in average, indicating about a 37% reduction compared to the conventional method.

Therefore, when the compromise method is applied, forest road slope area will be reduced compared to the conventional method. As bare land area caused by forest road facilities is reduced, run-off of soil from cutting and banking slopes and destruction of natural landscape may be mitigated.

4) Length of stabilization structure at forest road slopes

Slope stabilization structures that are set up for the mechanical stability of forest road slopes protects cutting and banking slopes as well as prevents forest road disasters and maintains a balance of cutting and banking volume within a forest road site. It also contributes to protecting facilities and land adjacent to forest road sites.

When the size, quality and length of slope stabilization structure are decided, mechanical relations should be considered based on slope status and size.

Figure 8 describes the length of sections that require slope stabilization structures for different survey & design methods. According to Figure 8, slope stabilization structures are set up in a section of 203 m/km (banking area: 182m/km, cutting area 21m/km) on average currently. However, when the compromise method is applied, slope stabilization structures need to be set up in a section of 415 m/km (banking area: 360 m/km, cutting area: 55m/km) on average, which is about 2.04 times more than the conventional method.

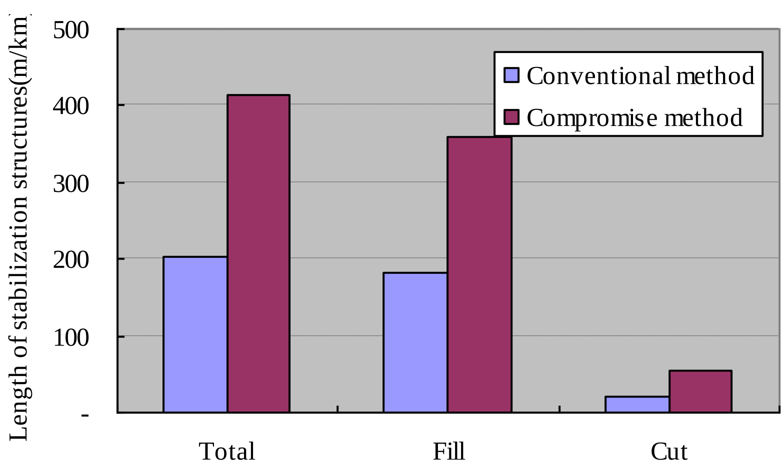

Figure 8. Length of stabilizations structures by survey methods

It is judged that in the case of the conventional method, slope stabilization structures were set up to their minimum extent due to lack of forest road facility budgets. When the compromise method developed in this study is applied, slope stabilization structure length was calculated assuming that stabilization structures would be set up in all slopes of which slope height is over 15 meters in order to protect privately owned plots nearby, maintain a balance of cutting and banking soil within the site and prevent disasters.

Given these, when the conventional survey & design method that applies the center-line method is improved by compromising zero-line method and center-line method, favorable forest road alignment is maintained. At the same time, the entire volume of cutting soil generated in a unit section is used as banking soil in the same section and transport distance may be minimized. Although the length of slope stabilization structure could be longer with the conventional method, the area of road prism could be less while most work loads, including cutting & banking volume, side ditch digging and forest road slope area could also be reduced.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Forest Resource Transportation Planning with Consideration of Forest Road Erosion*

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Abstract
This research incorporates an environmental impact of forest roads into an economic analysis for resource transportation planning. The Forest Service WEPP: Road, which is a road erosion prediction model, is combined with NETWORK 2000, an extensive economic forest transportation network planning model. WEPP is used to estimate the sediment delivery from each road segment to streams. Based on the estimated sediment delivery, NETWORK2000 produces alternative road systems that minimize both transportation costs and overall sediment delivery. This methodology is applied to the Mica Creek watershed in Northern Idaho. The results provide economically efficient and environmentally friendly alternatives for a forest road network in the watershed. The methodology and results are presented.

Keywords: road network design, network algorithm, environmental impacts, road management

1. INTRODUCTION

Research by forest land managers and technical specialists nation-wide indicates that forest roads are the greatest single source of sediment delivered to streams in forested watersheds (Burroughs 1991). Unfortunately, forest road networks are not currently optimized as a means to minimize sediment delivery to streams. This is partially because there is no method to directly incorporate sediment delivery into the economics of forest transportation planning.

The decisions people make about ecosystems imply valuations; and people choose whether to make these valuations explicit or not (Costanza et al. 1997). Forest transportation has been evaluated for environmental impacts (Girvetz and Shilling 2003), but has never had these impacts methodologically incorporated into an economic analysis with a monetary value. The logic of market failure has led economists, and increasingly scientists as well, to argue that the critical environmental resources need to be incorporated into the market system (Hanemann 1988).

Increased stream sedimentation, associated reductions in fish habitat productivity and mass road failures are just a few of the impacts that result from forest roads (USDA 1998). Sediment delivery from roads results from a combination of direct delivery at stream crossings, indirect delivery at culverts or other drainage structures, and from mass wasting events that deliver sediment to the stream channel (Madej 2001, Elliot et al. 1999). Studies have shown that the overall sediment produced in forested basins increases from road-related erosion processes (Wemple 2001).

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 221-232.*

This study was designed to develop alternative road network systems that minimize both the economic costs and environmental impacts represented by sediment yields for the Mica Creek Watershed in Idaho. Predicted sediment amounts from each road segment were estimated using the United States Forest Service (U.S.F.S.) WEPP: Road erosion prediction model (Elliot et al. 1999). The environmental costs were then calculated as a dollar amount per pound of sediment leaving the road and per pound of sediment delivered to the stream channel. The forest transportation economic analyses were carried out using the NETWORK 2000 forest transportation planning model. Based on the estimated sediment delivery, NETWORK 2000 produces alternative road systems that minimize both transportation costs and overall sediment delivery. Results for five different alternatives were attained; four results employed an environmental cost, and an optimal result with no environmental cost was found for comparisons.

The purpose of this study is to incorporate an environmental cost into an economic analysis that is used in forest transportation planning to reduce the undesired environmental impacts, while minimizing the economic costs. Putting a price on the environment is a controversial topic and has no existing standard method (Costanza et al. 1997). Our intention in this study is not to accurately estimate the environmental cost of sediment, but rather to analyze the effects of considering sediment into forest transportation planning with optimal road networks

2. STUDY AREA

The study area is located within the Mica Creek watershed, which is part of the St. Joe River Basin in Idaho, about forty-two miles southeast of Coeur d'Alene. Potlatch, a private timber company, owns and manages most of the watershed. The watershed is 13,046 hectares (32,238 acres) and includes 756 kilometers (470 miles) of roads. The study area is situated in the upper part of the Mica Creek watershed, and is 7,495 hectares (18,520 acres), or 58% of the entire watershed (Figure 1). The study area elevation ranges from 818 to 1,688 meters. The precipitation falls mostly in the form of rainfall with an average annual rainfall of 138.7 to 144.3 centimeters, and an average annual snow water equivalent of 0 to 63.8 centimeters of snow in the winter months (i.e. October - May) (NRCS 2002). The slopes are generally gentle in this area, but have some steep slopes up to 51.6 degrees. Parent materials consist of quartzite and schist (11%), quartzite (5%), siltite/argillite (16%), and siltite/quartzite (68%) (Potlatch 2005a). The quartzite has very low mass wasting potential and surface erosion potential, and the quartzite and schist has the highest. Eighty-nine percent of the soils in the watershed are silt loam, and the rest is sandy loam. Roads made up of surface soils that are of high clay or silt content have a higher surface area than roads that are of a rocky soil or that have a gravel surface. A higher surface area results in less infiltration of precipitation and greater overland flow. Thus, the roads containing surface soils of higher clay or silt content will generate more runoff and contribute more fine sediments to streams.

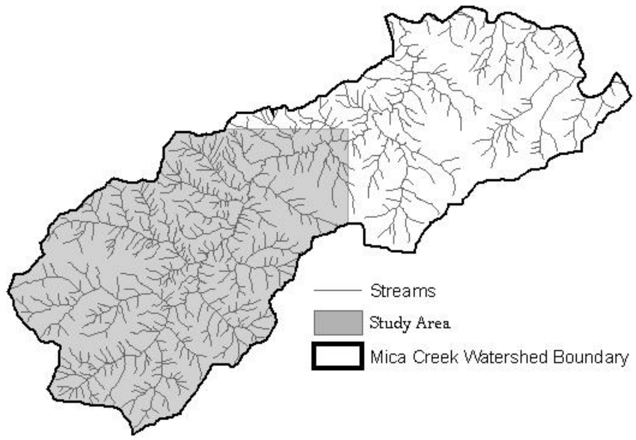

Figure 1. Study area in the Mica creek watershed in Northern Idaho.

There are 276 harvest units ranging from .4 to 77.3 hectares (1 to 191 acres) in size, and approximately 353 log landings. The total length of the entire road network analyzed in this study is 779 km (484 miles) and includes highways and local roads used to access the mills, and existing and proposed roads within the study area. The total road length estimated for sediment yield using WEPP:Road is 409 km (254 miles). Of these roads estimated by WEPP:Road 335 km (208 miles) is existing roads, and 74 km (46 miles) is proposed roads analyzed in this study for the future access needs to timber sale locations.

3. METHODS

A total of 3,889 sediment delivery points were identified throughout the field data collection and GIS analysis for surveyed, unsurveyed, and proposed roads. These delivery points represent stream crossings, drainage structure locations, or low elevation points along the road, where water collects and drains. These points were then used to split roads into multiple segments along with intersection points and high points on the road which divert water into two opposite directions. Sediment yields were then estimated from each road segment using WEPP:Road (Elliot et al. 1999), and converted into a dollar amount per pound. NETWORK2000 (Chung and Sessions 2003) was used to develop alternative road network systems that minimize both transportation costs and overall sediment delivery. Detailed methodology is described below.

3.1 Using WEPP:Road

The U.S.F.S. WEPP:Road erosion model predicts runoff and surface erosion from a road segment, and the sediment yield to an adjacent stream channel. This physically-based model was developed from the original Water Erosion Prediction Project (WEPP) model that predicts hillslope erosion (Elliot et al. 1999). Results from WEPP:Road consist of the mean annual sediment yield from the road surface and leaving the forest buffer or delivered to stream channels.

WEPP:Road assumes that there are three overland flow elements: a road, a fillslope, and a forest (Elliot et al.1999). Elliot et al. (1999) noted that runoff and erosion from these elements varies with climate, soil and gravel addition to the road surface, local topography, drain spacing road design and surface condition, and ditch condition. In order to provide the WEPP:Road model with information on these factors, the following input data are required:

- Road Segment Length (meters or feet)
- Segment Width (meters or feet)
- Segment Gradient (percent or degree)
- Surface Soil Texture: clay loam, sandy loam, silt loam, or loam.
- Road Design: outslope, outslope rutted, inslope vegetated or rocked ditch, or inslope bare ditch.
- Road Surface: gravel, native, or paved, and % rock content.
- Fill Slope (percent or degree)
- Fill Length (meters or feet)
- Buffer Slope (percent or degree)
- Buffer Length (meters or feet)

3.2 Field Data Collection

Using a Magellan Meridian GPS receiver, 1,298 points were surveyed along 136 kilometers (41%) of road within the Mica Creek Watershed. At each point during the survey, seven attributes were measured: road width, fill slope length, fill slope gradient, road design, road surface content, soil texture and percent rock content.

Locations of high points were recorded along with any road failures (i.e. debris flows, land slides, slumping). High points are essential to capture for situations where a high point in a road will direct water down in two distinct directions, and the elevation of the highpoint is needed to find the two segments gradients. These points were then displayed in ArcMap to acquire the rest of the spatial data and were linked with their specific attributes.

All stream crossings were recorded as delivery points but were noted as stream crossings in particular for later specifications in WEPP:Road. Sediment delivery was assumed equal to one hundred percent of the predicted erosion rate at stream crossings (Elliot et al. 1999). At stream crossings, fill and buffer attributes were assigned the lengths of 0.03 meter (0.1 foot), and slopes of 0.3%. Sediment leaving the buffer can be used for this estimate, although deposition on the fill or buffer may be overestimated (Elliot et al. 1999).

At each survey point along the road, surface soil texture was determined by hand. Soil texture was found to be similar throughout the study area and was compared to SSURGO Soil Survey database (NRCS 2003); to ensure differentiation of textures were accurate. Comparisons revealed little differences, and SSURGO data was then used for identifying soils for the non-existing proposed roads and roads that were not measured within the study area.

Climate data for WEPP:Road was generated from the St.Maries climate station approximately twenty miles from the Mica Creek Watershed. A fifty year simulation period was used for the WEPP:Road analysis to ensure that an adequate number of wet years was simulated.

3.3 Data Acquisition Using GIS

A 1 meter Digital Elevation Model (DEM) of the Mica Creek Watershed derived from LIDAR (Evans 2005) was used for GIS analyses in this study. Elevation and the length between each point were retrieved from the DEM. The data were used to find the segment gradient and the directional flow of runoff for each segment. The buffer slope and length were also retrieved from the DEM. Buffer lengths were measured from the delivery point location on the road to the nearest stream channel below and then the recorded fill slope length was subtracted from this. Buffer slopes were estimated using the elevation of the delivery point and the elevation of the nearest point on the stream channel below.

GIS data was used in post-sampling to provide replication of road segments from measured roads for 274 km (170 miles) of unsurveyed roads and proposed roads. Replication was focused on attributes such as road usage, slope, aspect, soils, geology and elevation. Replicated segments were assigned delivery points using the DEM. Using ArcGIS and the raster data from the DEM, the lowest points in elevation along the roads were located for every 90 to 150 meters depending on the averages applied to each road. These low points became the delivery points, as well as any stream crossings visible from the map in ArcGIS. High points were located after the delivery points to divide segments into the appropriate directional flow.

3.4 Other Assumptions for WEPP:Road

The WEPP:Road model predicts sediment amounts with a custom interface that assumes certain inputs. The soil properties for each soil texture are generalized from research findings. The road is assumed free of vegetation, the fill slope has around 50% ground cover, and the buffer contains forest litter of generally 100% (Elliot et al. 1999). Error to model predictions may result from using ArcGIS and assuming accuracy from a segment of road represented by an average gradient and width (Brooks et al. 2003).

3.5 Using NETWORK 2000

All of the predicted sediment amounts produced from WEPP:Road were incorporated into environmental costs, which were further combined with actual transportation costs and analyzed in NETWORK 2000 (Chung and Sessions 2003). NETWORK2000 is an economic analysis model for forest transportation that uses a heuristic algorithm for optimizing large fixed cost (road construction) and variable cost (timber hauling) transportation problems. It has been widely used by public agencies and forest industries to analyze alternative forest transportation routes and identify the least cost road network that connects timber sale locations (landing locations) to the mill.

NETWORK 2000 inputs are arranged by links, or road segments. These segments are identified by a beginning and ending node. Each link has a variable cost (hauling cost) which is defined by a road class factor (Table 1) multiplied by the length of segment. The variable cost units are set as dollar per thousand board feet (MBF) in this study. A fixed cost (road construction cost) can be also assigned to each proposed road segment. For proposed roads, a fixed cost is calculated and assigned using a construction cost of an assumed $40,225 per kilometer ($25,000 per mile) multiplied by the road segment length, where as zero construction cost is assigned to existing road segments. In addition, in order to include the environmental impact of each road segment in the model, the environmental cost for each road segment was added to the fixed cost as sediment yield in pounds multiplied by a cost factor (i.e. $25/pound and $50/pound of sediment).

Table 1. VARIABLE COST MULTIPLIERS

ROAD CLASS	MULTILPLIERS
PAVED HIGHWAY	$.60 / mile/ MBF
PAVED OR ROCKED LOCAL	$1.00 / mile/ MBF
PRIMARY	$2.00 / mile/ MBF
SECONDARY	$3.00 / mile/ MBF

Another required input data set for NETWORK 2000 is sale information. The harvest schedule provided by Potlatch Corp. was incorporated by identifying log landing point(s), harvest volume in MBF, year of harvest, and destination (mill) for each sale. Log landings and destination points are referred to as the entry nodes and destination nodes respectively. The harvest schedule from Potlatch for the Mica Creek Watershed is for seventy years, includes 276 harvest units, for 1,556 sales, and for 412 MMBF. The mills selected for the analysis are St. Maries, Medley Santa, and Clarkia, the three nearest mills to the Mica Creek watershed (Figure 2).

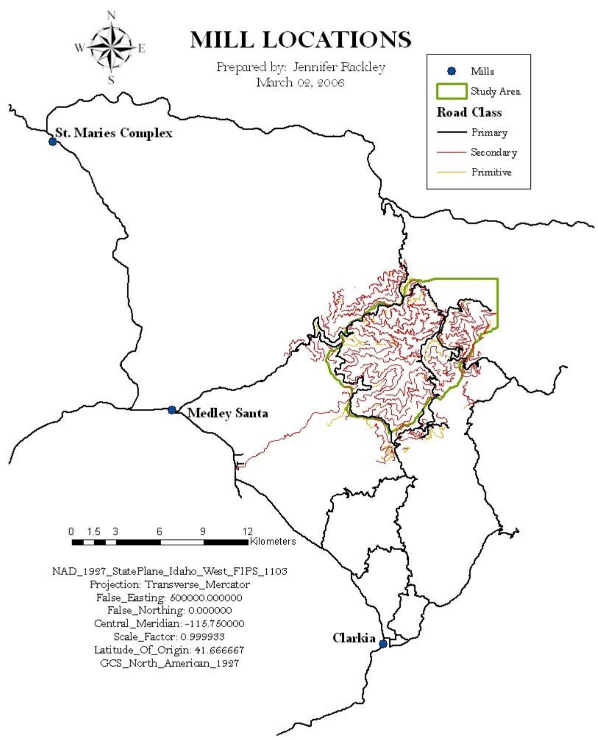

Figure 2. Road network in the study area.

3.6 Alternative Routes

NETWORK 2000 was run for the same harvest schedule for four different alternatives using environmental cost factors of $25 and $50 dollars per pound of predicted sediment yield, and for one with no environmental cost for result comparisons. The entire network of roads used for this program was 855 kilometers (531 miles), including all the primary, secondary, local roads, and highways that connect to the mills outside the watershed (Figure 2).

WEPP:Road gives two predictions, the annual sediment yield from the road segment surface and the annual sediment yield leaving the forest buffer or entering stream channels. Although the environmental concern is based from the sediment yield delivered to stream channels, to locate areas with high risk of potential erosion both of these predictions were used for the alternatives. The environmental cost factors were chosen without rationale other than to provide a scale for comparison.

Alternative 1 does not use an environmental cost and provides comparison of optimal routes and associated costs. Alternatives 2 and 3 use the predicted sediment yield leaving the road surface with the environmental costs of $25 and $50 dollars per pound of sediment. Alternatives 4 and 5 use the predicted sediment yield leaving the forest buffer or delivered to stream channels applied to the same two environmental costs factors. The alternative transportation routes that resulted from NETWORK 2000 are compared in terms of road construction and hauling costs as well as total sediment yields from each road network alternative.

4. RESULTS AND DISCUSSION

The WEPP:Road erosion prediction model results show 96% of the road segments evaluated have some sediment yield leaving the road surface, and 55% have some sediment yield leaving the forest buffer and delivered to stream channels. Results show an average of 2.12 tons per hectare (0.86 tons per acre) annually leaving the road surface, and an average of 1.57 tons per hectare (0.23 tons per acre) leaving the forest buffer and entering the stream channels for the entire study area (reported totals: 180.5 tons (397,853 lbs) from road surface; 49.2 tons (108,502 lbs) leaving forest buffer).

Five different alternative transportation routes were found from using the NETWORK 2000 program. For each alternative route a total variable cost, a total fixed cost and an overall network cost was reported (Table 2). The total variable cost is the total hauling cost, and the total fixed cost is the construction costs for proposed roads added with the environmental costs, and the total network cost is all of these added together. Whereas the total variable costs are more or less the same among the alternatives, the total fixed costs sharply increase as the environmental cost factors increase. The total variable costs do not vary much (3.9% at most) because the same timber volume, landing locations, and mill locations were used for all the alternatives. There are large changes in fixed costs because they consist of not only road construction costs, but also environmental costs which were represented by sediment yield multiplied by the cost factor.

Table 2. NETWORK 2000 results

ALTERNATIVES	Total discounted variable cost	Total discounted fixed cost	Total discounted variable and fixed cost
1	17,847,200.80 (43.30 $/MBF)	835,475.17 (2.03 $/MBF)	18,682,675.97 (45.32 $/MBF)
2	18,152,716.43 (44.04 $/MBF)	6,507,286.90 (15.79 $/MBF)	24,660,003.33 (59.82 $/MBF)
3	18,598,029.59 (45.12 $/MBF)	11,936,801.59 (28.96 $/MBF)	30,534,831.18 (74.07 $/MBF)
4	18,006,340.75 (43.68 $/MBF)	2,178,595.28 (5.29 $/MBF)	20,184,936.04 (48.97 $/MBF)
5	18,079,219.76 (43.86 $/MBF)	4,314,265.26 (10.47 $/MBF)	22,393,485.02 (54.32 $/MBF)

To compare total network costs of all the alternatives only the total variable cost and the associated construction costs from the total fixed cost are used (Table 3). The actual construction cost shown in Table 3 is the total reported fixed cost minus the associated environmental cost since it is not an actual monetary value. Table 3 also shows the total length of roads chosen in each road network alternative with the total sediment amounts estimated leaving road and delivered to streams from the alternative.

Table 3. Comparisons of actual costs and predicted sediment delivery

Alternatives	Environmental Cost	Hauling Cost (millions)	Construction Costs (thousands)	Total Network Cost (millions)	Total Road Length (km)	Total Sediment Leaving Road (tons)	Total Sediment Delivered to Stream Channels (tons)
1	NONE	17.9	841.6	18.7	388.8	162.9	44.5
2	$25 / lb.	18.1	827.4	18.9	374.1	103.1	32.1
3	$50 / lb.	18.6	853.3	19.5	375.8	100.6	30.4
4	$25 / lb.	18.0	873.9	18.9	380.2	109.5	32.2
5	$50 / lb.	18.1	875.7	19.0	386.5	106.4	31.7

The hauling costs are the same as the variable costs from the NETWORK 2000 output, and have an increasing trend with the increase of each environmental cost factor. The construction costs are the fixed costs from the NETWORK 2000 output minus the associated environmental costs for each alternative and do not vary by more than 5.8%. The total network cost in Table 3 is the hauling cost added to the construction costs for each alternative, and also has an increasing trend with the increase of the environmental cost factors. Total actual costs for all five alternatives do not vary by more than 4.3%.

The results show a slow increase in total cost and the rapid decrease in sediment yield, with the increase of the environmental cost factors for the alternatives. Although the environmental concern is the amount of sediment leaving the forest buffer and delivered to stream channels, the alternatives using the WEPP:Road sediment prediction from the road surface (alternatives 2 and 3) were found to have a lesser amount of sediment delivered to stream channels than same cost factors from alternatives 4 and 5. This is because 96% of the total road segments evaluated by WEPP:Road have some sediment yield predicted to be leaving the road surface and only 54% of the segments have a predicted sediment yield delivered to stream channels. This means that 96% of the segments had an environmental cost for finding the alternatives 2 and 3, and only 54% of the segments had an environmental cost for finding alternatives 4 and 5. All road segments that have a predicted sediment yield delivered to streams also have a predicted sediment yield from the road surface. But not all segments that have a predicted sediment yield from the road surface have a predicted sediment yield delivered to streams. Therefore, minimizing sediment yield for more road segments (i.e. Alternatives 2 and 3) results with less sediment yield delivered to streams.

Alternatives 2 and 3, and alternative 1 show a decreasing trend in sediment yield with the increase of the environmental cost factors, for both the total sediment yield leaving the road surface and delivered to stream channels (Table 3). Alternatives 4 and 5 and alternative 1 also show a decreasing trend in sediment yield delivered to stream channels with the increase of the environmental cost factors (Table 3).

Overall trends can be seen in the percent increase in cost from alternative 1 versus the percent decrease in predicted sediment yields (Figures 3 and 4). The trend follows a slow steady increase in cost with a rapid decrease in sediment yields. The total network costs for all the alternatives are within $0.8 million dollars of the total network cost for alternative 1 or maximum 4.3% increase in cost compared to alternative 1. However, these four alternatives produce at least 53.4 tons less sediment yield (or 33% decrease) than alternative 1 for sediment predicted leaving the road surface, and at least 12.3 tons less sediment yield (or 28% decrease) than alternative for predicted sediment amounts leaving the forest buffer and delivered to stream channels. These results indicate that a relatively large amount of sediment can be reduced at the expense of a slight cost increase.

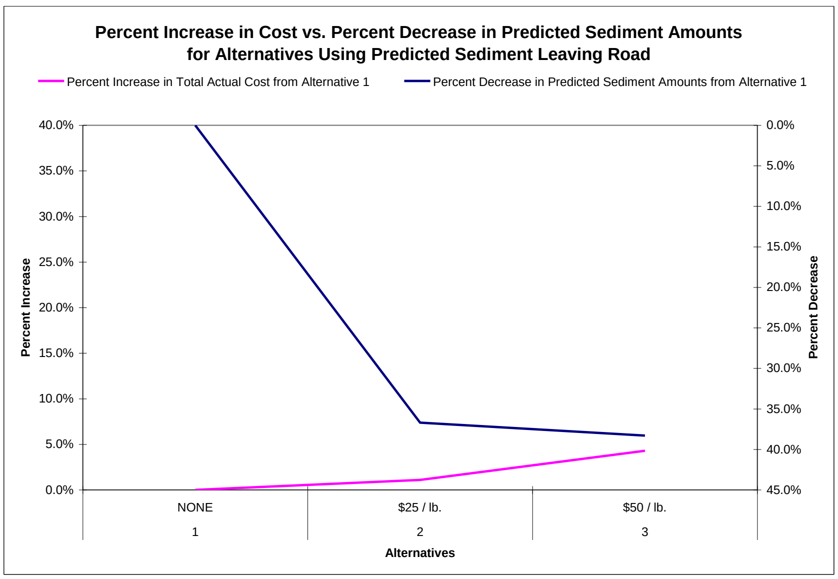

Figure 3. Rate of cost increase with sediment yield decrease for alternatives 1 through 3 using sediment yield from road surface

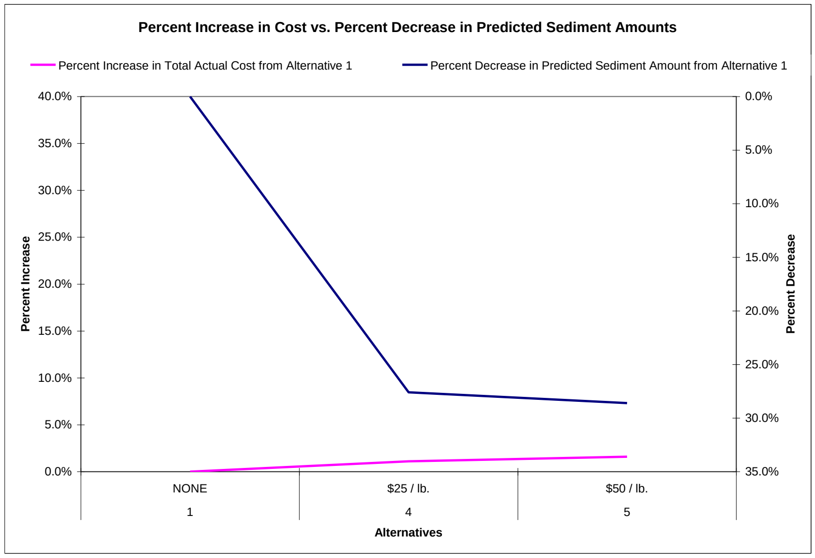

Figure 4. Rate of cost increase with sediment yield decrease for alternatives 1, 4 and 5 using sediment yield delivered to stream channels

In finding these five alternatives, at least 50% of the 779 kilometers (484 miles) of current total road network length can be reduced while maintaining access to each stand for future harvesting activities. These alternatives at the very least can guide Potlatch forest managers in locating roads that are unnecessary and roads identified having a high risk of erosion. The roads deemed unnecessary will continue to cause environmental impacts if left untreated and abandoned. Erosion rates remain higher than background levels as long as roads remain in place, making them a chronic sediment source (Parker 2005).

Roads that are identified to have a potential high risk of erosion can increase maintenance costs and the associated environmental impacts. Road design improvements such as increasing the drainage structures and decreasing distance between structures can be used to reduce this risk. Seeding and mulching of new culvert installations, slides and areas of disturbed soil and/or areas of potential erosion problems is another way to decrease the risk of erosion (Potlatch 2005b).

5. CONCLUSION

Combining WEPP:Road with the NETWORK 2000 program resulted in the development of improved road networks that consider environmental impacts as well as overall costs. The environmentally considerate alternatives were able to reduce sediment yields by as much as 39% from Alternative 1 and increase the cost by 4.3% at most. The roads that were evaluated and determined to no longer have an economic use in this watershed could be closed, decommissioned, or obliterated upon the decisions of Potlatch forest managers. The results indicate that our approach to incorporate environmental impacts into transportation planning can generate alternative road networks that minimize both transportation costs and overall sediment delivery from the network.

A large amount of data was needed to successfully run the U.S.F.S. WEPP:Road and the NETWORK 2000 models together, but has shown to be an effective method of evaluating a large watershed with only a portion of field data needed. GIS knowledge of raster data from a DEM is required to accurately, and efficiently retrieve the data for these two models. The use of a 1 meter DEM is recommended for more accurate elevation and slope data, but may be difficult and/or expensive to attain. This transportation planning method was not replicated and should be used for the Mica Creek Wathershed only as guidance for decision making on road management.

This method does not currently consider maintenance costs, but incorporating the maintenance schedule and costs into this method would be more realistic in road management and could significantly improve the results. Results would also improve based on a more realistic economic cost associated with each road segment for NETWORK2000.

There is no set method for choosing an appropriate environmental cost factor for predicted sediment yields from the road surface and delivered to stream channels. A forest manager would need to assess the final network costs for all the alternatives relative to budget constraints, maintenance costs, willingness to reduce sediment yields at the expense of increasing costs, and would also need to assess the conditions of the actual routes in the field. These alternatives at the very least can guide Potlatch forest managers in locating roads that are economically unnecessary and roads having a high risk of erosion. The integration of an environmental cost into the NETWORK 2000 economic analysis not only improves the economic efficiency of the transportation network, it adds conservation to forest transportation management.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Automatic road-network planning for multiple objectives*

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Abstract
Automatic planning of forest road networks is an on-going, challenging task. Advances have been triggered by the increased availability and accuracy of digital terrain models, greater computing power, and improvements in optimization techniques. Defining one's objective functions is a crucial step in guiding the design process and controlling optimization. However, the problem still exists for mapping the fitness of design alternatives to valuable, spatially explicit figures for one or more of those functions. This paper aims (1) to present system models that map the spatial variability of three objective functions (construction and maintenance costs, negative ecological effects, and the suitability, or attractiveness, for cable-yarding landings); and (2) to evaluate the effects of this multi-objective problem on Pareto-optimal solutions. We have taken two approaches for articulating our objective preferences (*a priori* "choice before search" and *a posteriori* "search before choice") as well as two optimization methods (graph algorithms and a heuristic search). Our results show that (1) the Steiner minimum tree solutions are located on convex trade-off surfaces, as expected from the multi-objective optimization theory; (2) single-point solutions are clustered on the Pareto frontier, such that small changes in the relative weights of objective-function components can trigger movement from one cluster to the next; and (3) allocation of relative weights to those components greatly affects the solution.

Keywords: cable-yarder attractiveness, ecological impact, graph optimization, Pareto optimum, preliminary road-network planning, Steiner minimum tree

1. INTRODUCTION

Designing the optimal road network is difficult to do across a varying landscape (Scaparra and Church 2005). Engineers must consider several related problems: (1) an overwhelming amount of terrain and environmental data, (2) a lack of explicit constraints, and (3) unclear and contradictory goals. Computer-aided engineering approaches have been developed for solving these layout problems (Kirby 1973, Mandt 1973, Dykstra 1976), and their utility has been accelerated by the widespread availability of digital elevation models. Initially limited by computing power, they have been improving continuously, resulting in software packages such as PLANS (Twito et al. 1987), PLANEX (Epstein et al. 1999, 2001), and CPLAN (Chung and Sessions 2002a). However, even the most sophisticated methods have some shortcomings: (1) they assume road-building costs to be route-independent, (2) they limit the number of possible links from a specific network node to its adjacent nodes, (3) they assume the road centerline to be a chain of consecutive straight lines without considering curve or switchback constraints, and

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 233-248.*

(4) they rarely analyze systematically the trade-offs between different objective functions. Previously, we reported improvements on the first three shortcomings, and presented a route-dependent cost estimation model (Stückelberger et al. 2004, 2006) and an improved link-pattern. Here, we introduce an approach to forest road layout that overcomes the last shortcoming - the lack of systematic analysis for trade-offs in multiple objectives.

Real-world engineering optimization problems are inherently multi-objective because they normally have several, possibly conflicting, goals that must be satisfied simultaneously (Stadler 1988). Rarely is there a single point that optimizes all the objective functions concurrently. Most optimization algorithms rely on a scalar fitness function to guide the search. The most intuitive approach is to combine the multiple objectives into a single function via the "weighted sum of objective functions methods" (Coello 2000, 2001). Weighting factors map the preferences of a decision maker, and can be allocated in two ways: (1) *a priori*, where the trade-offs to be applied are defined before the optimization methods are run, and (2) *a posteriori*, where the decision maker chooses the solution by examining possible options computed by optimization methods (Collette and Siarry 2004). *A posteriori* methods produce, at the end of the optimization process, a trade-off surface. Most previous approaches to road layouts used a mono-objective configuration that minimized some cost functioning. Only a few contributions were based on a bi- or multi-objective problem, and were implemented very efficiently by the "weighted sum of objective functions" approach. Nevertheless, it is possible, by varying the value of the weights, to approximate the trade-off surface. One obvious problem with this approach, however, is that it may be difficult to generate a set of weights that properly scales the objectives when little is known about the problem. Another, more serious, drawback is that this approach cannot generate proper members of the Pareto (1896-1897) optimal set when the frontier is concave (Coello 2001, Collette and Siarry 2004). The goals presented here include: (1) the development of a system model that maps the spatial variability of three objective functions (life-cycle costs, concurrent ecological effects, and the suitability, or attractiveness, of cable-yarder landings; and (2) an evaluation of the Pareto frontier for this objective configuration at specific test sites. We first describe the methodology and then provide an assessment of optimal road layouts for different mono- and multi-objective configurations.

2. METHODS

2.1 Objective functions

The resolution of problems concerning realistic road-route layouts requires the simultaneous optimization of more than one objective function. Solutions must be (1) physically feasible, (2) economically efficient, (3) environmentally sound, and (4) institutionally acceptable. Physical feasibility is usually guaranteed by constraint formulations on the solution space, whereas economic efficiency and environmentally soundness have to be simultaneously maximized. Our aim is to solve the following problem: find a minimum spanning tree that connects mandatory points in mountainous terrain. Here, "minimum" refers to simultaneously and efficiently reducing life-cycle costs and the likelihood of selecting unattractive landing locations, as well as minimizing the disturbances to habitat and rare ecotopes. The four components of this objective function are specified below.

Estimating construction costs

Cost estimation is the most decisive factor when planning the layout of low-volume forest road networks. Stückelberger et al. (2006) have developed a model that estimates the spatial variability of road life-cycle costs. This overall model has five components: (1) a digital elevation model (DEM), (2) classification for geotechnical properties of the subsoil, (3) the specification of road design parameters, (4) unit costs for structural components, and (5) a rock-excavation share model (Figure 1). Historically, this method has been superior to estimates based on expert knowledge, and is believed to be the only procedure for modeling the spatial variability of roading costs in large, mountainous areas.

Estimation of adverse ecological effects

It is a normative decision to select a set of adverse ecological effects. Decision preferences also vary in space and time, making it difficult to compare different approaches. In our investigation, we have considered two types of environmental impacts – habitat quality for the capercaillie (*Tetrao urogallus*) and marshland biotopes.

Capercaillie, the largest mountain grouse in middle Europe, is threatened with extinction (Keller et al. 2001). Its requirements for forage, cover, reproduction, and comfort are crucial variables that define habitat suitability (Bollmann 2003). We have used Graf's (Graf et al. 2002) habitat suitability index (HSI; US Fish and Wildlife Service 1981) to measure capercaillie habitat quality. Disturbances are assumed to be proportional to road length and HSI (Ulber 2004). For example, a 100-m-long road segment that crosses a capercaillie habitat with a suitability index of 0.2 results in an impact cost of 20, which is considered equivalent to a 20-m road segment that might cross a habitat with an HSI of 1.

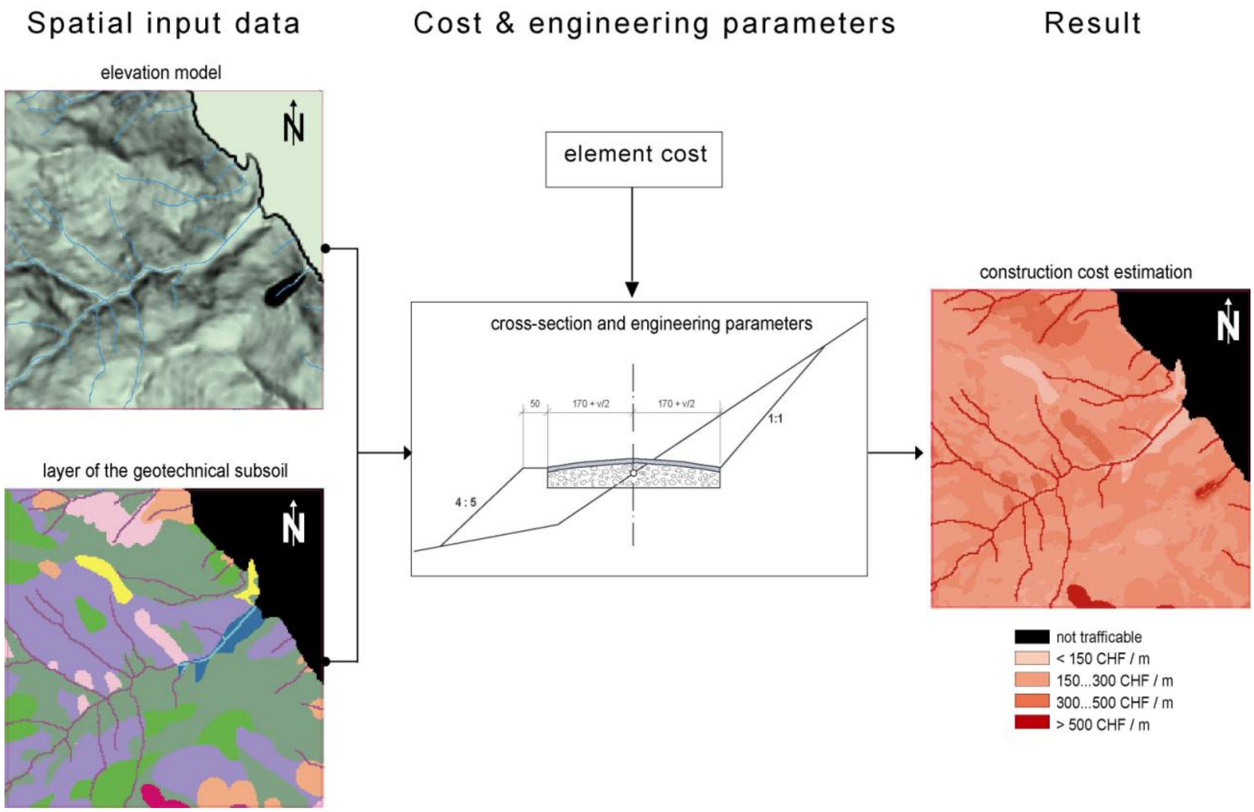

Figure 1. Flow-chart for potential road construction cost estimation.
Area of Wägital (Switzerland), 2 km x 2 km.

Marshland areas, including upland moors, reeds, and wetlands, are important ecotopes that are protected by Swiss legislation. Determining their ecological value is difficult. Government agencies have established a standard evaluation procedure that considers the size of the area, the number of different vegetation types, and diversity (BUWAL 1991). Several adverse effects on marshlands must be weighed. First, road construction directly disturbs such areas due to sealing of the surface. Second, it can cause indirect disturbance by influencing the flow of groundwater (Marti et al. 1997). Third, a road can dissect a marshland biotope, leading to fragmentation (Jaeger 2002). Therefore, we have introduced outside and inside buffer zones, each 100 m wide (Figure 2). The inside buffer zone and the center zone are assumed to have habitat values based on the considered worth of the ecotope (Ulber 2005), whereas the habitat value of the outside buffer zone is assumed to decrease from that value to zero. Marshland disturbance is presumed to be proportional to road length and ecological value. If a road enters the center zone, an additional penalty is added to the disturbance factor, thereby representing the fragmentation effect.

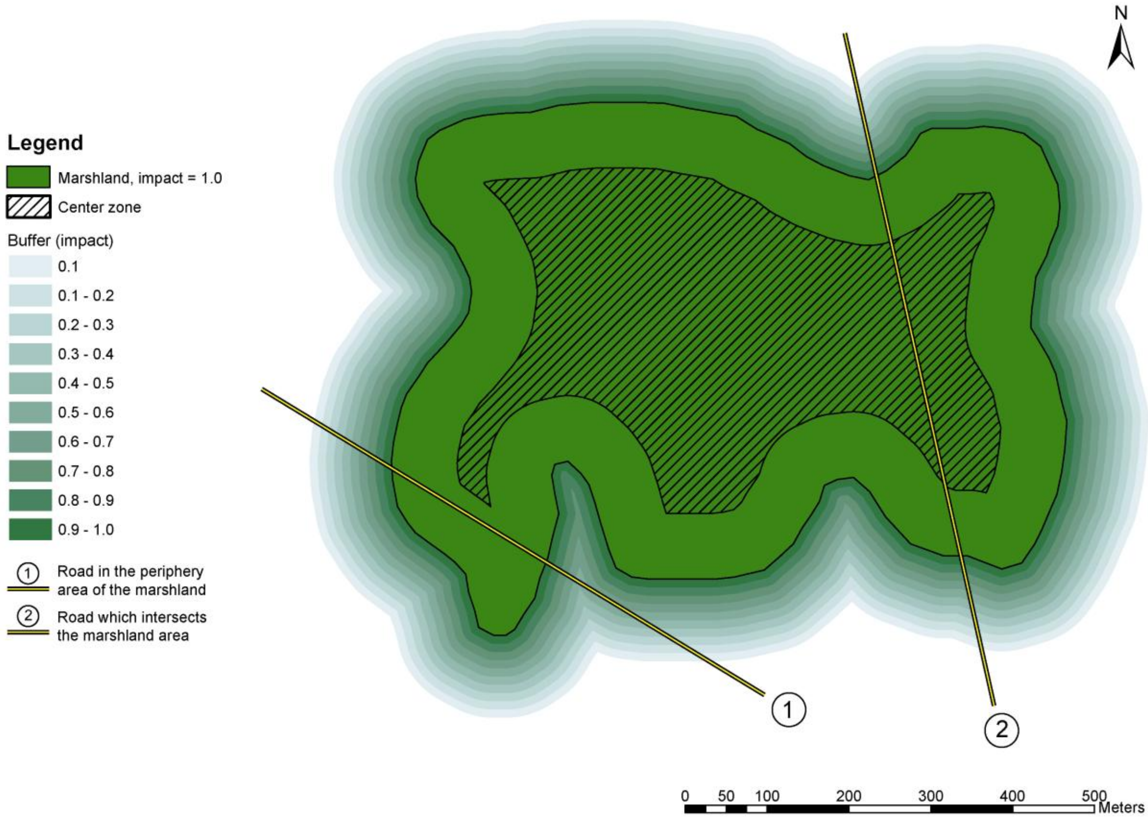

Figure. 2. Marshland area with buffer and central zones. Road (1) affects the marshland in the buffer zone and periphery only, whereas Road (2) additionally influences the marshland because of the intersection effect. (schematic draft)

Attractiveness of cable-yarder landings

Positioning of the landing locations influences the efficiency of off-road transportation, especially for cable-based extractions. A road should not only connect mandatory access points, but also reach favorable landings. We, therefore, have introduced a landing-attractiveness factor that considers both effectiveness and efficiency of the cable yarder in operations (figure 3). This factor is calculated according to the following procedure:

1. select a raster cell as a potential landing location (L)
2. for $\alpha = 0°$ to $345°$ (in 15° increments):
3. determine the tailspar point (T) for maximal skyline length,
4. determine the terrain profile,
5. for any point between T and L:
6. calculate ground clearance of the cable road,
7. when ground clearance is < 0, then
8. move T one unit in the direction of L.

9 fix location T,

10. connect all T-points,
11. calculate area bounded by T-points (figure 4),
12. weight the area with the timber volume to be harvested, and

13. repeat 1 to 12 until all raster cells are evaluated.

Step 12 can also be modified slightly by weighting the potential logging volume by a factor that represents the installation and logging conditions (e.g., the number of intermediate supports (I) and logging direction).

A powerful model (CableAnalysis 1.0) is available for automatically determining the landings for cable logging (Chung and Sessions 2002b, 2003, Chung et al. 2004). We have incorporated this model into our procedure for calculating attractiveness for the cable yarder.

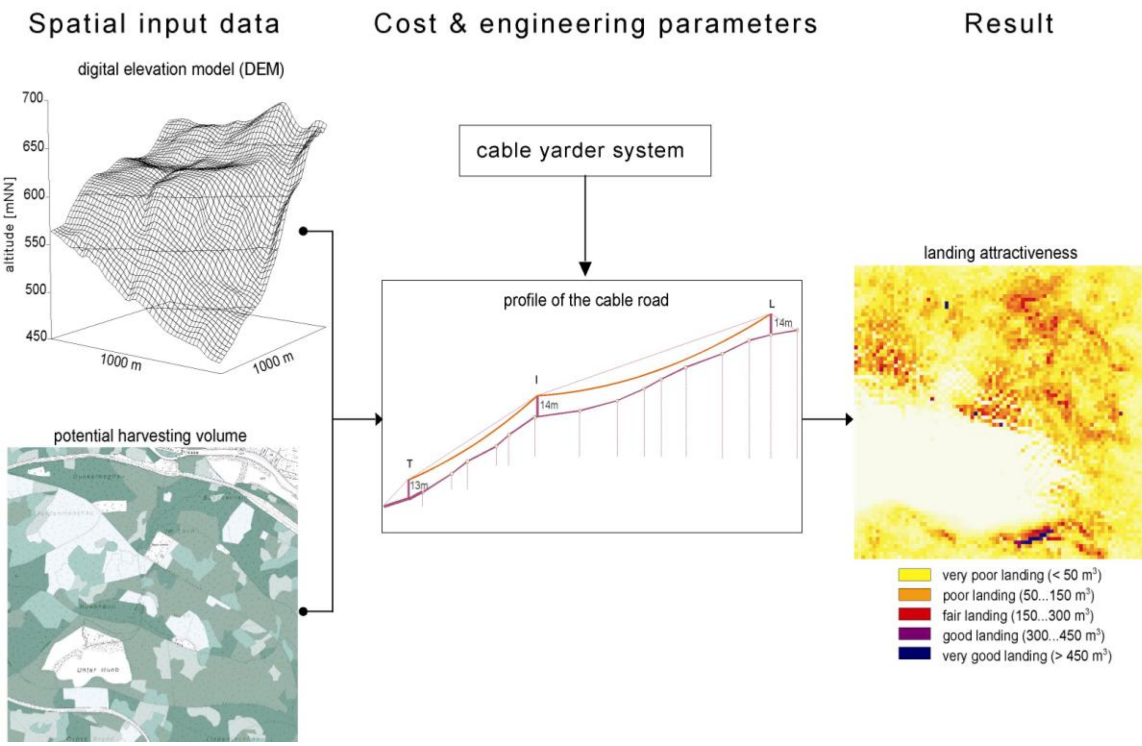

Figure 3. Flow-chart for calculating cable-yarder attractiveness.
Area of Üetliberg (Switzerland), 1 km x 1 km.

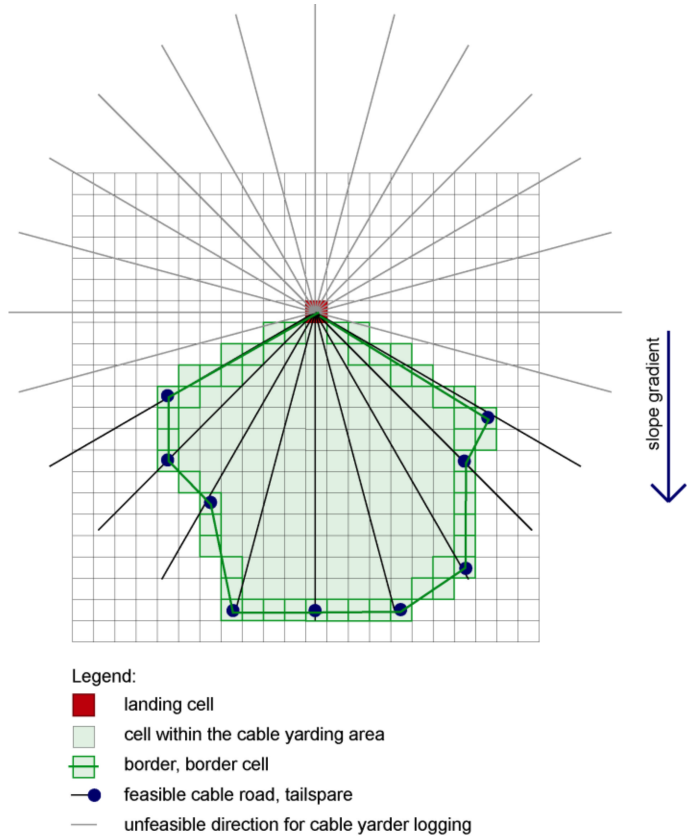

Figure 4. Cable-yarder landing and its overspanning harvesting area. (schematic draft)

2.2 Multi-objective optimization

Multi-criteria optimization is rooted in late-19th century welfare economics, as described by Edgeworth (1881) and Pareto (1896-1897). A feasible solution to a multiple objective problem is considered Pareto-optimal if no other feasible solution is at least as good for every objective function or performs worse than at least one other. This means that no objective component can be improved without other components being made worse. Typically, there is an entire curve or surface of Pareto points, whose shape indicates the nature of the trade-off between different goals (Figure 5). Multi-objective problems are very often solved by combining all components into one scalar objective function [Equation 1]. The prevailing approach consists of minimizing the weighted sum of function components, which is called "an *a priori* definition of the multiple-objective function". With this approach, the decision maker defines the trade-off to be considered and explicitly expresses his or her preferences before running the optimization model.

[1] $$O_x = \sum_{i=1}^{k} w_i \times f_i(x)$$

where,

x	=	object x
O_x	=	aggregate fitness of object x
k	=	number of different objectives
w_i	=	weighting factor of objective i

$f_i(x)$ = i^{th} objective function for object x

It is up to the user to choose appropriate weights, which are extremely decisive for the solution that will result from the optimization process. The main shortcoming of this "*a priori*" approach is that the solution represents only one point on the Pareto frontier, and trade-offs are not evaluated and understood. In contrast, an "*a posteriori*" optimization aims at tracing the complete Pareto frontier curve for each multi-objective case, thereby producing $n^{(k-1)}$ evaluation cases. The eventual computational effort is extremely high, necessarily restricting the analysis to only a small subset of the solution space.

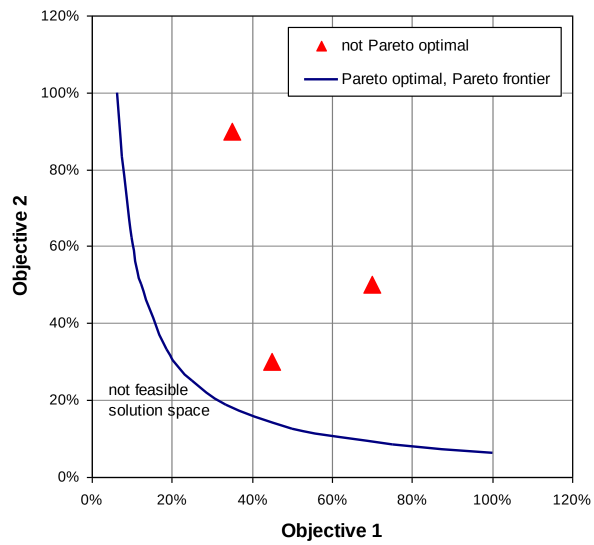

Figure 5. Solution space with Pareto optima of 2 objectives.

"*A posteriori*" preference methods investigate a set of solutions that results from systematic variation in the weights of the objective-function components. At the end of the optimization, those methods produce a trade-off surface, i.e., the Pareto frontier. Given two objectives, O_1 and O_2, that must be minimized simultaneously, many Pareto frontiers in real-case studies describe a hyperbolic function derived with Equation [2], and defined by parameters *a, b, c,* and *d*. Often, parameter *a* is set to 1.

[2] $$y = \frac{c}{x^a + b} + d$$ where, $x = O_1$ and $y = O_2$,

2.3 Graph model for road-network system

Road engineers control the geometry of a layout by following a sequence of vectors, known as a 'traverse'. The road is then designed as a series of curves inside the angles between consecutive vectors, straight segments along vectors, and curves outside the angles between successive vectors that define hairpin bends (Ervin and Gross 1987). A geographical area is the continuous physical entity on which we can define an infinite number of points for use as the start- and end-points of vectors. However, graph optimization algorithms require a finite set of nodes (vertices) and links (edges). Therefore, the specification of the design space follows the concept of discretization, i.e., splitting a continuous physical system into a discrete set of simple shapes.

The prevailing approach uses either grid or graph representations. Road directions in the former are limited to the eight neighboring grid cells. In contrast, a graph representation is not limited to a regular grid structure, and allows more and different road directions. The aim of a graph model is first to generate a mesh of all possible links over the entire project area, then find the best subset of the graph that represents the optimal forest road network.

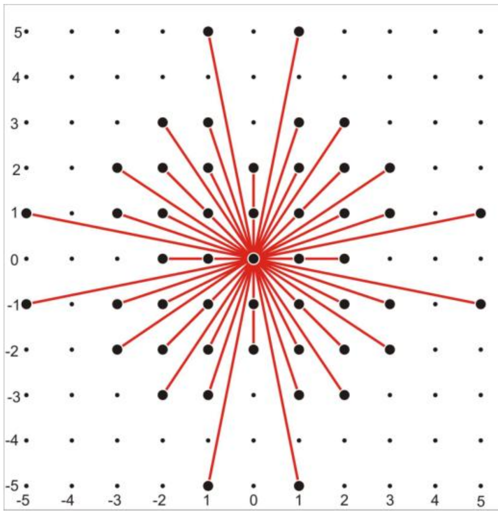

Figure 6. Neighborhood patterns of one center node to 48 neighboring nodes.

Our model employs a graph representation. However, our nodes are arranged in a regular structure representing the central point of each raster cell of the DEM. In contrast to a standard grid representation, road links (edge) are not defined between neighboring grid cells only, but also are found within an enlarged neighboring area (Figure 6). This extension of neighborhood is very important, especially in steep terrain (Stückelberger et al. 2004).

Optimization techniques

The problem here is to find the minimum spanning tree that links all mandatory control points. The solution requires a sequence of analytical tasks:

- identify a feasible set of links,
- calculate and assign the weight for each feasible link,
- use Dykstra's algorithm (Dijkstra 1959) to calculate the shortest paths (SPs) for any subset of two control points,
- find the minimum spanning tree (MST), using the SP to all mandatory control points (terminals), according to Prim's algorithm (Prim 1957), and improve the solution by introducing Steiner points (Prömel and Steger 2002) to identify the Steiner minimum tree (SMT).

SP and MST algorithms are well documented (Cprogramming.com 2005a, b). The problem of introducing Steiner points is more difficult. In a graph with *n* nodes, *n-2* Steiner points may be incorporated to improve the solution and find the Steiner minimum tree. Unfortunately, there is no algorithm to locate those Steiner nodes within polynomial time, making this problem NP-hard (i.e. Non-deterministic Polynomial-time hard). If the size of the project area and the number of terminal points are limited, it is possible to determine the mathematical optimum for the SMT by testing all combinatorial possibilities. For larger problems, however, the use of heuristics is an efficient approach to obtain at least near-optimal solutions. Simulated annealing (Kirkpatrick et al. 1983), the heuristic we have adopted here, produces solutions that are within a couple percentage points of the optimum.

3. MODEL EVALUATION AND RESULTS

3.1 Evaluation of layout

Different configurations of the multi-objective function are evaluated in order to optimize route layouts. Here, we have analyzed three configurations: (1) mono-objective, (2) Pareto frontier, and (3) bi-objective with weight variations. Although our graph model follows the 48-link pattern (Figure 6), a Steiner minimum tree optimization procedure is used.

Our first test site is at "Wägital", a 35-km² area on the northern slopes of the Swiss Alps. This region is characterized by steep terrain (average slope gradient of approximately 35%), difficult geotechnical conditions, a dense water channel network, and high-value ecotopes and habitats. It, therefore, is an ideal model for investigating multiple, conflicting objective conditions.

3.2 Mono-objective optimization results

The "Wägital" area has 10 mandatory control points (Figure 7). The problem to be solved is to find an SMT that minimizes costs, impacts on capercaillie habitat, and harm to marshland ecotopes. The key parameters in our cost-optimal solution (Scenario 1; Table 1) consist of a 10-km-long road network with a life-cycle cost of 6.6 million Swiss francs (CHF). Adopting eco-optimal solutions that conserve both capercaillie habitat and the marshland ecotope results in a longer road network and higher costs. When those potential impacts are evaluated separately and compared with our cost-optimal data, the capercaillie-optimal solution (Scenario 2) involves a 62% longer road network and 84% higher costs. Likewise, the marshland-optimal solution (Scenario 3) requires an additional 18% in road length and a 32% increase in costs, compared with the cost-optimal solution. These results demonstrate the conflicting nature of two ecological objectives. The capercaillie-optimal solution not only incurs longer roads and greater costs, but also increases the impact on marshland ecotopes by about 65%. Overall, the impact of the marshland-optimal solution is three-fold greater than that of the capercaillie-optimal solution. The main difference in length and cost for capercaillie-optimal versus marshland-optimal solutions, based on our Steiner minimum tree network (Figure 7), arises because a long detour is required for bypassing capercaillie habitat in the northern part of the project area.

Cost versus ecology trade-offs

The determination of the Pareto frontier is based on stepwise changes in the relative weight of objective-function components. Here, we have evaluated the trade-off between cost minimization and the lowest ecological impact. The eco-component is a scalarization of the two eco-objectives, minimization of capercaillie habitat impacts and minimization of marshland ecotope impacts. Relative weights of these two components change within a range from zero to 1000. Our Pareto frontier evaluation (Figure 8) is bound by two extremes: (1) the cost-optimal solution (at the upper-left end), and (2) the eco-optimal solution (lower-right end). These numbers represent the relative weight between the eco- and the cost-components of the objective function. One might assume the Pareto points to be evenly distributed along that frontier. How-

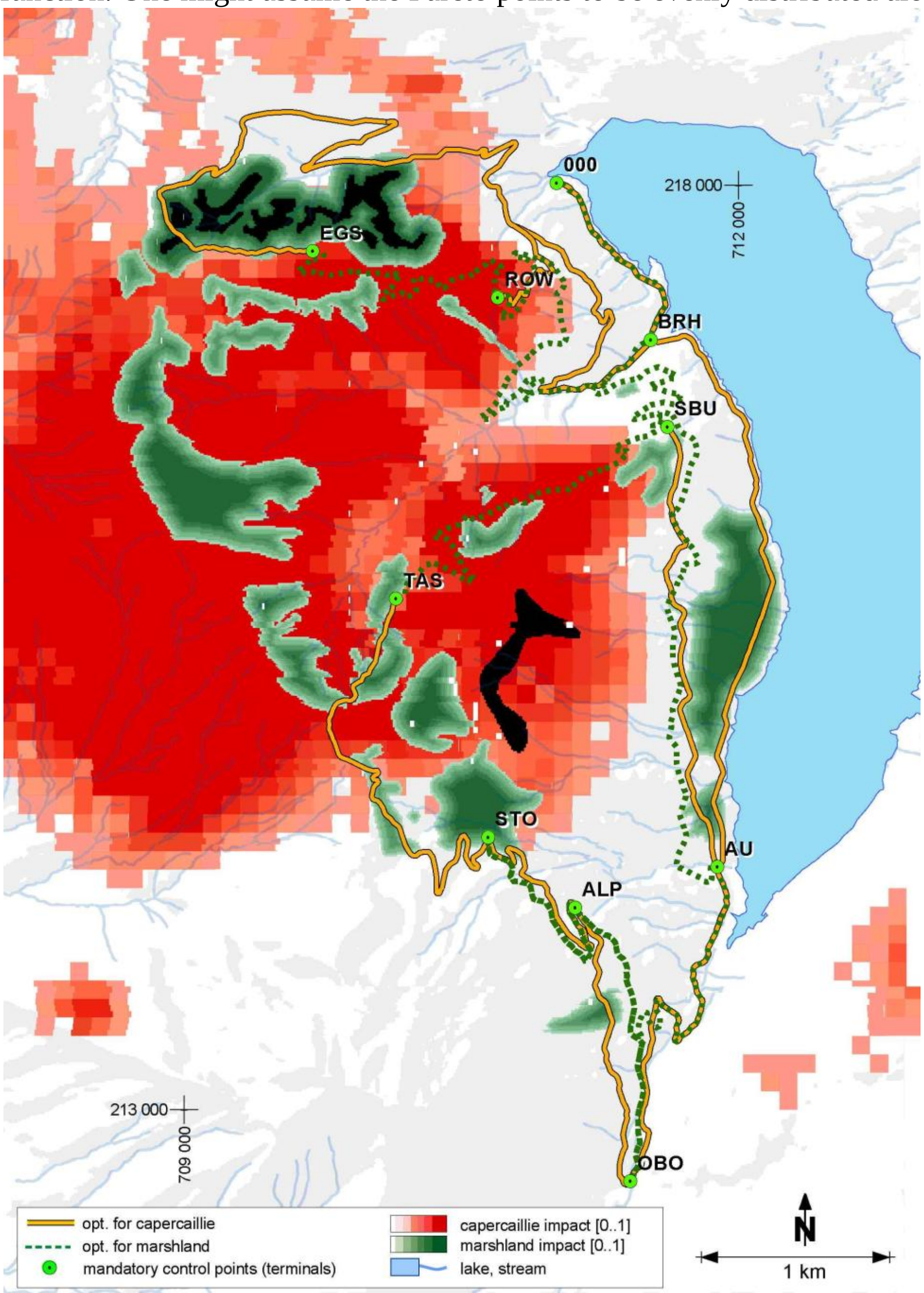

Figure 7. Road network (SMT) for Scenarios 2 (capercaillie-optimal) and 3 (marshland-optimal) between 10 mandatory control points. Background: ecological value of capercaillie and marshland, streams, lake, and hillside. Project area of Wägital (Switzerland), 5 km x 7 km.

Table 1. Key parameters and their associated costs when comparing road networks among optimized scenarios.

Scenario	Road length [m]	Net present value [CHF]	Net present value relative	Capercaillie impact [m*I]	Capercaillie impact relative	Marshland impact [m*I]	Marshland impact Relative
1) Cost-optimal	19'001	6'630'831	100%	6'221	285%	1'677	80 x
2) Capercaillie-optim.	30'827	12'216'567	184%	2'184	100%	2'776	132 x
3) Marshland-optimal	22'439	8'771'925	132%	7'279	333%	21	1 x

ever, the Pareto-optimal solutions are concentrated on three clusters: (1) a cost-optimal cluster, with relative weights of 0 to 4, (2) a cost-eco-balanced cluster, relative weights of 5 to 350, and (3) an eco-balanced cluster, relative weights of 400 to 1000. The Pareto frontier has two discontinuities at which the solutions are "jumping": first, at the weight change from 4 to 5, and second, from 350 to 400. The Pareto points (Figure 8) are located on a hyperbola (parameters a = 1, b = -0.62, c = 0.182, and d = 0 [Equation 2]), and the optimization results truly lie at the Pareto frontier. The spatial layouts for the cost-optimal, cost-eco-optimal, and eco-optimal solutions are shown in Figure 9. These evaluation results improve our understanding of the trade-offs.

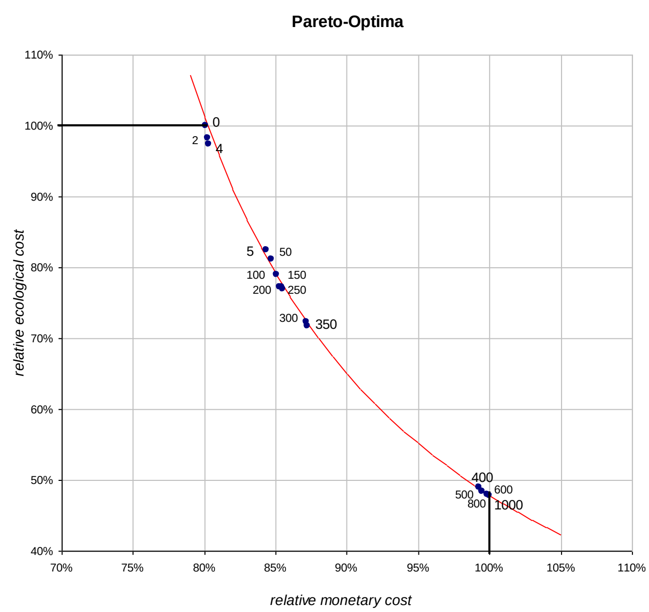

Figure 8. Pareto-optimal solutions and Pareto frontier of monetary and ecological costs. Area of Wägital, Switzerland.

3.3 Trade-offs between costs and landing attractiveness

In evaluating the trade-off between minimizing costs and maximizing of landing attractiveness for cable yarding, determination of the Pareto frontier is based on a stepwise change in the relative weights of two objective-function components. The problem to be solved here is to connect three control points in the "Uetliberg" project area (Figure 10). Relative weights change between zero and two. The Pareto frontier (Figure 10) is bound by the cost-optimal solution (upper left) and the attractiveness-optimal solution (lower right). One assumes that a stepwise change in relative weight would be manifested in corresponding steps on the Pareto frontier. Nevertheless, relative weights between zero and 0.65 result in a cost-optimal cluster with a road length of about 1.85 km and a landing attractiveness of about 150%. In contrast, a relative weight of 0.7 is associated with approx. 33% longer roads and a landing attractiveness of about 250%. This discontinuity is caused by a change in route location between points B and C. A further increase to 1 for relative weight alters the route between points A and B, such that relative road construction costs rise by 170% and the relative landing attractiveness is enhanced by 360%, compared with our construction cost-optimal solution. Raising the relative weight from 1 to 2 produces marginal improvement in landing attractiveness but also increases construction costs considerably. Figure 11 illustrates the spatial layouts of our different Steiner minimum trees.

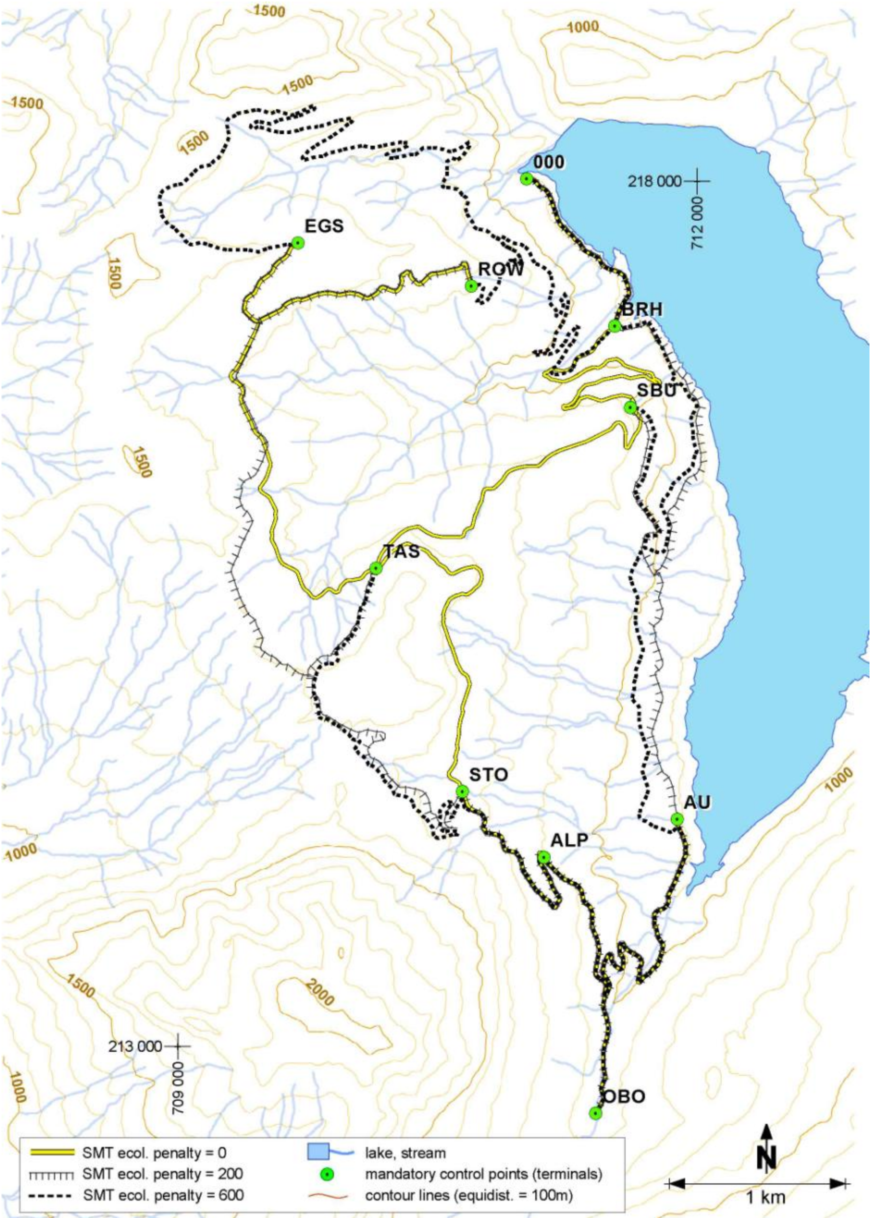

Figure 9. Road networks (SMT) for cost-optimal, balanced, and ecological-optimal scenarios between 10 mandatory control points. Background: contour lines, streams, and lake. Project area of Wägital (Switzerland), 5 km x 7 km.

4. DISCUSSION AND CONCLUSIONS

This paper presents models for mapping the spatial variability of three objective functions in forest road design (life-cycle costs, adverse ecological effects, and landing attractiveness). The effects of this multi-objective problem on Pareto-optimal solutions were evaluated at various test sites. Three major findings have emerged from this investigation. (1) The Steiner minimum tree solutions are located on convex trade-off surfaces, as predicted by the multi-objective optimization theory. (2) Single-point solutions are clustered on the Pareto frontier; even small changes in the relative weights of objective-function components can trigger jumping from one cluster to the next. (3) The allocation of relative weights to those components greatly influences the solution.

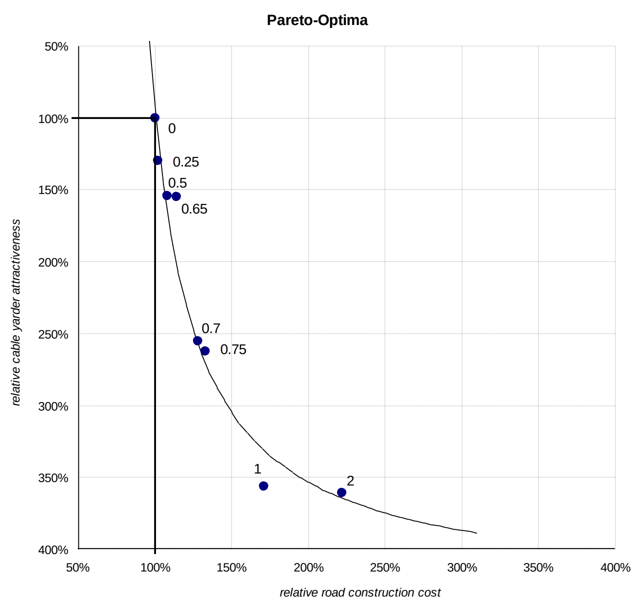

Figure 10. Pareto-optimal solutions and Pareto frontier of road construction costs and cable-yarder attractiveness. Area of Uetliberg, Switzerland.

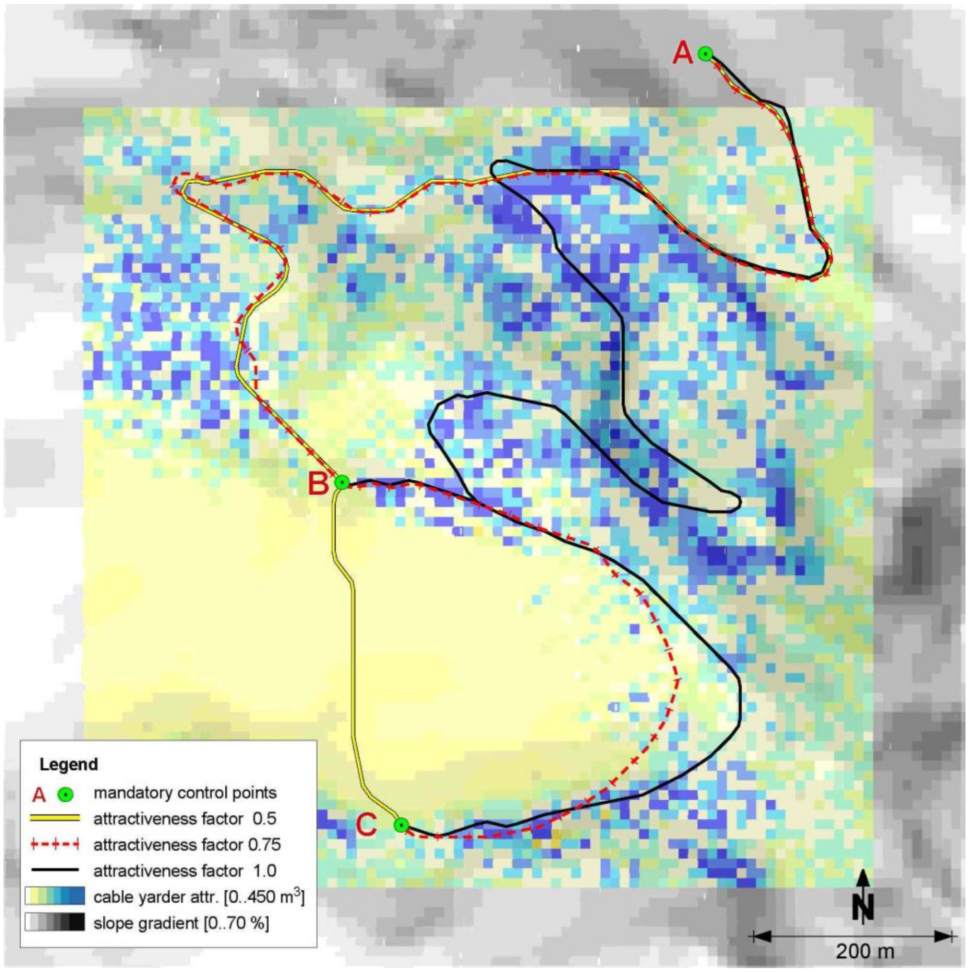

Figure 11. Road networks (SMT) for 3 different objective functions (weighting factors for cable-yarder attractiveness: 0.50, 0.75, or 1.00) between 3 mandatory control points (A, B, and C). Background: slope gradient and cable-yarder attractiveness. Project area Uetliberg (Switzerland), 1 km × 1 km

To our knowledge, this is one of the first analyses of the trade-off surfaces for multidimensional objectives that optimize the layout of road networks at a 10 m x 10 m resolution. Problem-solving in the open space is characterized by a set of partially conflicting requirements brought forward by different stakeholders. Mono-objective analysis evaluates the edges of the solution space that characterize those varying points of view.

In our example, the landowner was interested in a cost-optimal solution, whereas ornithologists would prefer our capercaillie-optimum and marshland specialists would look for the marshland-optimum. Therefore, mono-objective results are a good starting point in the negotiation process because they quantify the effects of extreme preferences on the different objectives. Systematic variations in the relative weights of the objective-function components are a prerequisite for exploring the Pareto frontier. The evaluation presented here clearly improves our understanding of problem-specific trade-offs and identifies solution clusters. Only three clusters resulted from the 10 mandatory control points analyzed in this Steiner minimum tree problem. It seems a likely supposition that the number of solution clusters would increase with the number of mandatory control points. Obtaining a Pareto solution by *a priori* "choice before search" is only permissible if a problem is repeatedly solved for many different weighting factors, a task that can tremendously multiply computational efforts.

Our approach also has some shortcomings. Whereas a cost metric may adequately map a real-world situation, our ecological impact metric is based on expert knowledge that considers some weak, unclear components, which one must be aware of when interpreting these results. A basic assumption of multicriteria-optimization is that objective values must be independent. However, our landing-attractiveness metric violates this assumption because it allocates accessible, though overlapping, areas to each grid cell. Nevertheless, this approach seems to be useful in controlling the location of routes for specific off-road transportation technologies (e.g., ground-based, cable-based, or airborne).

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Sediment Travel Distances below Drivable Drain Dips in Western Montana*

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Abstract
Sediment delivery to streams from unpaved forest roads consists of direct delivery from road segments leading into stream crossings and indirect delivery below drainage outfalls. The indirect component of sediment delivery depends on the distance that sediment travels downslope as well as the road erosion rate. Several studies have quantified sediment travel distances in highly erodible parent materials such as the quartz monzonite of the Idaho Batholith, but less research has been conducted in other parent materials. We investigated sediment travel distances below drivable drain dips along unpaved roads in the metasedimentary Belt Series and glacial till parent materials of western Montana. In the Belt parent materials, sediment travel distances ranged from 0 to 58.2 m (n = 139, mean = 4.0 m), but 78% of the sites had a travel distance of < 5m and 24% had a travel distance of zero. Similarly, in glacial till parent materials, travel distances ranged from 0 to 33.4 m (n = 148, mean = 3.2 m) while 76% of sites had a travel distance of < 5m and 40% had no detectable sediment below the dip. These travel distances are lower than those measured in granitic parent material, both in this and other comparable studies. Due to the limited sediment travel distances, most drainage outfalls in these parent materials do not contribute sediment to streams. Indirect sediment delivery is most likely to occur at drainage outfalls near to stream crossings or if the road erosion rate is unusually high. Sediment delivery from existing roads can be effectively reduced by: 1) positioning the first drivable dip such that the sum of direct and indirect delivery is minimized, 2) installing slash filter windrows below drainage outfalls, 3) closing unused roads, and 4) grading road segments near stream crossings only as necessary to avoid the formation of ruts.

1. INTRODUCTION

Unpaved roads are a primary sediment source in forested watersheds in the western United States (Megahan and Ketcheson, 1996; Megahan and Kidd, 1972; Brake et al., 1997). Sediment delivery to streams from unpaved forest roads consist of a direct component, which is the sediment delivered from road segments leading into stream crossings, and an indirect component which is the sediment delivered at constructed drainage outfalls and where road surface runoff flows off the road tread before reaching a ditch or drain. Improved knowledge of the direct and indirect components of sediment delivery can be used to reduce the impact of roads on streams and other aquatic habitat through improved road system planning and better management and maintenance of existing roads.

The sediment delivery ratio from road segments leading into stream crossings is close to 100%, so that the direct component of sediment delivery depends almost entirely on the road

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 251-263.*

erosion rate. Road erosion rates vary with road age, road design and maintenance, parent material characteristics, and the intensity and timing of road use (Sugden and Woods, *in press*; Packer, 1967; Reid and Dunne, 1984). Erosion rates are highest in the first year after road construction, when the road surface and cut and fill slopes are unvegetated and sediment availability is high (Brake et al., 1997), but decline rapidly as sediment availability decreases and vegetation cover on the cut and fill slopes increases (Burroughs and King, 1989; Ketcheson and Megahan, 1996). Higher erosion rates occur on steeper, longer road segments due to the greater stream power associated with overland flow on the road tread. Roads in highly erodible parent materials, such as feldspar-rich granitic rocks, can have erosion rates that are many times higher than in less erodible parent material. Roads that receive more use, such as mainline haul roads, have higher erosion rates because vegetation establishment on the road tread is limited and periodic grading to maintain the road surface increases sediment availability (Brake et al., 1997). Active hauling on roads during wet periods results in particularly high erosion rates.

The delivery ratio for indirect sediment delivery is less than 100% because a portion of the sediment eroded from the road is stored on the hillslope as a plume of sediment that lies on top of the natural soil profile. Since indirect sediment delivery only occurs if the sediment plume intersects a stream channel, the delivery rate depends on the distance that sediment travels downslope. Studies conducted in granitic parent material have shown that the sediment travel distance varies with the road erosion rate, the transport capacity of road runoff, and the amount of storage available on the hillslope (Megahan and Ketcheson, 1996). Road segments with a high erosion rate tend to have longer travel distances because of the greater volume of sediment delivered to the hillslope (Megahan and Ketcheson, 1996). The higher sediment volume fills up storage elements on the hillslope, leading to a greater cumulative travel distance. Insloped roads have higher sediment travel distances because road surface runoff is concentrated in the ditch and at drainage outfalls, providing greater transport capacity for eroded sediment (Megahan and Ketcheson, 1996). Similarly, longer, steeper road segments have longer travel distances because of the increased flow depth of the surface runoff. Hillslope roughness is an important control on sediment travel distances because of the greater amount of sediment storage available in depressions and behind rocks, branches and logs (Haupt, 1959).

Sediment delivery to streams from existing road networks is managed through voluntary Best Management Practices (BMPs) and designation of streamside management zones (SMZs). BMPs reduce the basic erosion rate and the extent to which runoff is concentrated at drainage outfalls, route sediment onto hillslopes where it is more likely to be held in long term storage, or act as a physical barrier to the downslope movement of sediment. For example, drivable drain dips divert run-off from the road tread onto the hillslope below the road, so reducing overland flow distances and the resultant erosion (Logan, 2001). Drivable dips are popular because they are relatively inexpensive to install, and because they can be retro-fitted to existing roads. However, these and other road BMPs such as ditch relief culverts, open top culverts, and flapper water bars are only effective if they are located so that the sediment travel distance below the drainage outfall is less than the distance to the nearest stream. Similarly SMZs, which act as a vegetative filter strip that reduces runoff and sediment delivery to streams from the adjacent upland, are only effective in reducing sediment delivery if the sediment travel distance is less than the SMZ width. Selection and location of appropriate road BMPs and designation of adequate SMZ widths requires knowledge of sediment travel distances in a range of environments.

Extensive research has been conducted on road erosion and sediment travel distances in highly erodible parent materials such as the granitics of the Idaho batholith (Megahan and Kidd, 1972, Megahan et al., 2001; Burroughs and King, 1989), and the high precipitation and landslide prone climate of Oregon's Coast Range (Wemple et al. 1996, 2001; Luce et al. 1999, 2001; Brake, et al. 1997). However, there has been much less comparable research in less erodible parent materials such as the Belt Series and glacial tills of western Montana. Given the current state of watershed assessments, TMDL load allocations, and road system planning and management, there is a need for more precise, parent material specific sediment travel distance data. The objectives of this study were to: 1) quantify sediment travel distance and plume volume below drivable drain dips along roads in Belt and glacial till parent materials in western Montana; and 2) develop recommendations for more effective BMP implementation and road system management to reduce sediment delivery. The data and analysis reported in this study should assist land managers to more accurately assess, identify, and mitigate sediment impacts from forest roads in the northern Rockies.

2. STUDY AREA

Study sites were located within seven townships in western Montana where Plum Creek Timber Company (PCTC) is the primary landowner. PCTC owned roads within the six townships have a native surface and due to the general absence of subsurface flow interception they typically do not have an interior ditch and drivable dips are used to route overland flow from the roadbed. Most of the PCTC road system is at least ten years old and the cutslopes and fillslopes are generally well vegetated. The frequency of maintenance operations varies depending on the level of use for log hauling and other forest management activities.

Parent materials in three of the townships are primarily quartzite and argillite beds belonging to the Missoula Group of the Belt Supergroup (Winston, 1986). Rocks of the Belt Supergroup underlie approximately 75% (31.5 million km^2) of western Montana (Ross, 1963). Soils within the three Belt townships comprise primarily loamy-skeletal, mixed, frigid Udic Ustepts of the Winkler Series (USDA, 1995). In another three of the townships, the soils are formed from glacial till deposited by the Pinedale glacial episode. Tills, outwash and glacio-lacustrine sediments deposited by Quaternary continental and alpine glaciers are the dominant parent material in much of the northern part of Montana (Johns, 1970). Soils in the three glacial till townships comprise loamy-skeletal, mixed Andic Cryepts of the Waldbillig Series. The seventh township lies in the upper Lolo Creek watershed near the Montana – Idaho border, and is underlain by quartz-monzonite granitic rocks. Data from the seventh township were collected to validate the study methodology and to provide a comparison with similar studies conducted elsewhere in granitic terrain (e.g. Ketcheson and Megahan, 1996).

Western Montana has a continental-maritime climate in which topography is the primary control on precipitation and temperature. Mean annual precipitation in the vicinity of the six study townships ranges from 600 mm to 1000 mm per year (USDA Soil Conservation Service, 1981), and as much as 70% of this precipitation can fall as snow. Approximately 95 percent of the annual rainfall erosivity is due to convective storms that occur between May and September (Renard et al., 1997). Summers are warm, and maximum daily temperatures above 35 ^{o}C are not uncommon. The coldest month of the year is January, when much of western Montana experiences sub-zero daily maximum temperatures.

3. METHODS

3.1 Sediment Travel Distance

Sediment travel distances were measured at 139 drivable drain dips in the Belt Series townships, 148 in the glacial till townships and 50 in the granitic township. Drain dips were randomly selected from the population of all dips on PCTC roads within each township. A GIS was used to randomly select road segments in each township, ranging in length from less than 10 meters to hundreds of meters. Road segments were visited in the order designated by the random selection process, and a maximum of five drain dips was surveyed in each road segment. If a road segment contained more than five dips, the first five dips encountered traveling upslope were surveyed. The majority of drain dips in the study area were installed between five and fifteen years prior to this study. Sediment travel distance below each dip was defined as the straight-line distance from the toe of the road fillslope to the lower limit of observable sediment deposition. The lower limit of deposition was defined by excavating with a hand trowel along the axis of the plume until road sediment deposited above a buried O or A horizon was no longer visible.

3.2 Factors Controlling Sediment Travel Distance

Eight independent variables were measured at each sample site to determine the factors controlling the sediment travel distance (D, m): road type (ROAD, mainline or spur), elevation (E, m), road vegetation cover (V, %), segment length (L, m) and gradient (S %), road shape (SHAPE, %), hillslope gradient (HILLSLOPE, %), and hillslope roughness index (R, dimensionless). R was defined in accordance with (Morgan, et al. 1993) as:

$$R = \left(\frac{M - S}{M}\right).100$$

where M = ground microtopographic distance along plume axis (m)
S = straight line distance along plume axis (m)

The ground microtopographic distance included rocks, sticks, and logs that were in contact with the ground surface. Low growing bunch grasses were included in the measurement but live woody-stemmed understory vegetation was not included due to its minimal effect on sediment storage and overland flow.

3.3 Sediment Plume Volume

Sediment plume volume was measured at five Belt Series sites and four glacial till sites using a simplified version of the procedure described by Ketcheson and Megahan (1996). The objective was to determine the plume geometry as a function of distance downslope, and to relate plume volume to the sediment travel distance. At each site, the sediment plume was divided along its longitudinal axis into ten slices, and each slice was divided into six "cells", aligned parallel to the plume long axis. At the center of each cell the depth of the deposited road sediment was measured and recorded. Total plume volume estimates were calculated by summing the individual cell volumes.

3.4 Particle Size Analysis

Sediment samples from the contributing road surface and the corresponding sediment plume were collected at the ten sediment plume volume sample locations to ascertain the change in sediment particle size distribution between road tread and sediment plume. These data were used to evaluate the percentage of fines transported beyond the measured plume length. Particle size analysis was conducted using the modified hydrometer method (Gee and Bauder 1986).

3.5 Data Analysis

Sampling locations were stratified by parent material and by road type and an analysis of variance (ANOVA) was used to determine whether there were significant differences in sediment travel distance between sites in the Belt Series and glacial till and between sites on mainline haul roads and spur roads. Sediment travel distance was normalized using a $\log_{10}$ transformation. Multiple regression was used to assess the effect of the eight independent variables and two generated variables (LS, the road length-slope product, and LS^2, the length-slope squared product) on the sediment travel distance in each parent material. Previous studies have indicated that LS and LS^2 can be a more significant predictor of sediment travel distance than length or slope alone (Luce and Black, 1999). ROAD was defined as a categorical variable where a value of 1 represents a mainline road and 2 represents a spur road. Values for R, L and LS were log transformed prior to analysis to improve the normality of the data. Pearson correlation analysis was used to identify the variables that were significantly correlated with sediment travel distance and with each other. Only the most significant variable in a group of correlated variables was included in the regression modeling. A step-wise approach was used to develop the most appropriate regression model using these variables.

4. RESULTS

4.1 Sediment Travel Distance

Sediment travel distances at the Belt Series sites ranged from zero to 58.2 m, with a mean of 4.0 m. All except one of the sites had a travel distance of less than 24 m, 78% had a travel distance of less than 5 m and 24% of the sites had no detectable sediment below the outfall (Figure 1). In the glacial till sites, travel distances ranged from zero to 33.4 m with a mean of 3.2 m. Seventy six percent of till sites had a travel distance of less than 5 m and 40% had a travel distance of zero. Sediment travel distances measured in the granitic parent material ranged from zero to 28.7 m, with a mean of 5.4 m. Ketcheson and Megahan (1996) obtained mean values of 3.8m and 8.7m for sediment travel distances below fillslopes and rock drains, respectively in granitic terrain, indicating that the methodology used for the present study is valid and that comparisons with studies conducted elsewhere are appropriate.

Mean sediment travel distances in the Belt and glacial till parent materials were not significantly different ($P>0.05$). However, mainline roads had a significantly higher mean sediment travel distance than spur roads in both parent materials ($P < 0.05$). This is likely due primarily to greater vegetation cover on the spur roads and the resultant reduction in the road erosion rate. Spur roads had almost five times and more than three times the average road tread vegetation cover than mainline roads in Belt and glacial till sites, respectively, and the differences were statistically significant in both cases. In the glacial till sites, spur roads were also significantly less steep than mainline roads ($P < 0.01$) and this may have contributed to the lower sediment travel distance.

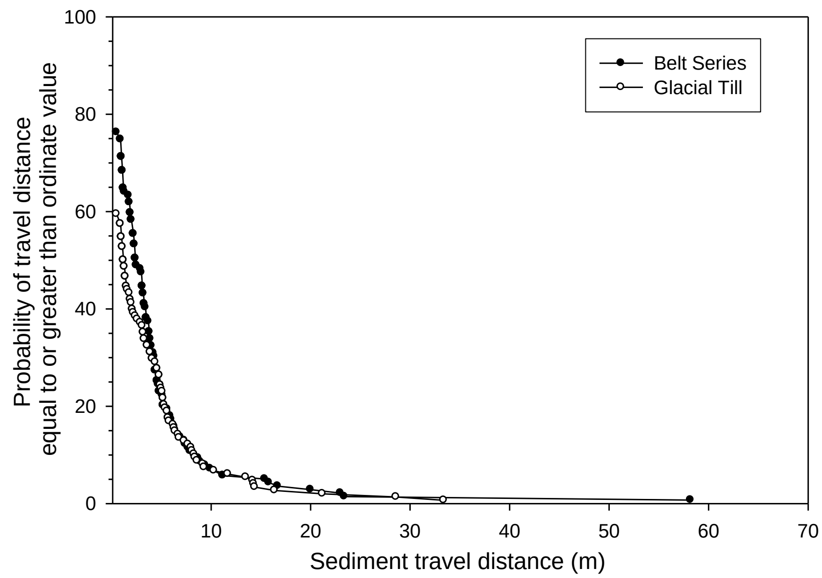

Figure 1. Percent exceedance probability for sediment travel distances below drivable dips on roads in the Belt Supergroup and glacial till soils of western Montana.

4.2 Sediment Travel Distance Correlation and Regression Analysis

In the Belt Series sites, the variables E ($P = 0.027$), V ($P = 0.038$), L ($P = 0.005$), log L ($P = 0.003$), S ($P=0.047$), SHAPE ($P = 0.001$), log RI ($P = 0.008$), LS ($P=0.002$), LS^2 ($P = 0.003$) and log LS ($P = 0.019$) were all significantly correlated with the logarithm of sediment travel distance ($\log_{10}$ D). Most of the independent variables representing road length and slope were correlated with one another, so that only LS was used in the step-wise regression modeling. The resulting model:

$$\log_{10}(D) = 0.977 + 0.226 \times 10^{-4} (LS) - 0.174 (ROAD) - 0.289 \log RI$$

is significant ($P < 0.001$) and explains 23% of the variability in sediment travel distance.

The site variables obtained from the till sites had considerably less predictive capability than those in the Belt Series sites. Only S ($P = 0.037$) and log LS ($P = 0.045$) were significantly correlated with the logarithm of sediment travel distance. Segment slope (S) was omitted from the multiple regression model because it was significantly correlated with LS and was a less significant predictor of sediment travel distance. Consequently, the only variables used in the regression analysis for till sites were road type and log LS. The resulting model:

$$\log_{10}(D) = 1.013 - 0.282\ (ROAD)$$

is significant (P = 0.001) but it explains just 11% of the variability in sediment travel distance.

4.3 Sediment Plume Volume

Sediment plume volumes were generally small, with 6 of the 9 plumes containing less than 0.5 m^3 of road sediment. In the Belt Series sites plume volume ranged from 0.07 to 6.2 m^3 with a mean of 1.4 m^3. The largest plume volume in the Belt sites was an outlier, and occurred at a site which had one of the longer sediment travel distances, 7.6m. In the till sites the plume volume ranged from 0.12 to 0.56 m^3 with a mean of 0.4 m^3.

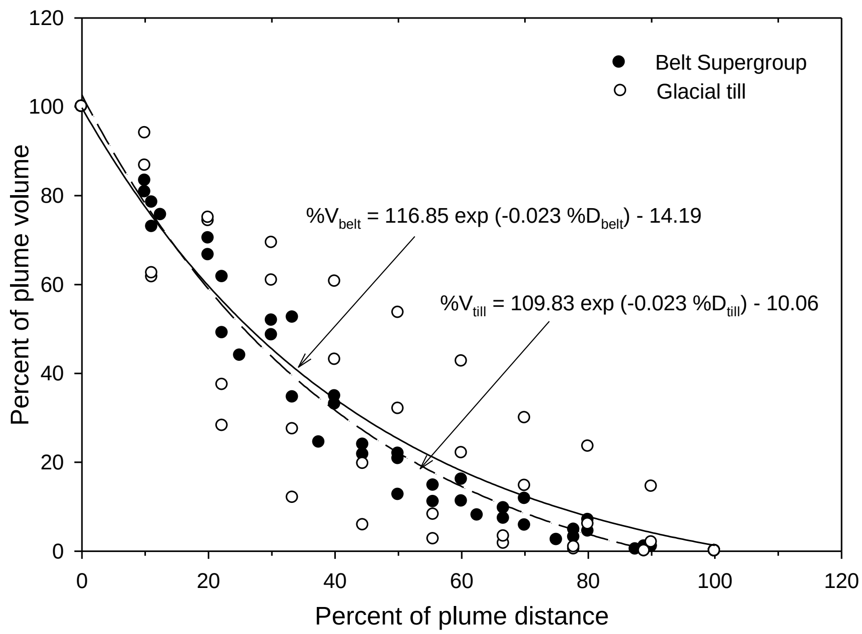

Figure 2. Cumulative percent plume volume versus cumulative percent of total travel distance for sediment plumes below drivable dips in the Belt Supergroup and glacial till soils of western Montana

Sediment plume volume rapidly diminished with increasing distance from the fillslope toe such that, on average, 80% and 75% of the plume volume occurred in the upper half of the plume in the Belt Series (R^2 = 0.98, std. error = 4.83) and glacial till sites (R^2 = 0.82, std. error = 15.0), respectively (Figure 2). These results are consistent with work conducted in granitic sites in central Idaho, where 84% of the plume volume occurred in the upper half of the plume (Ketcheson and Megahan, 1996). Plume volume was highly correlated with sediment travel distance in both parent materials (R^2 = 0.90, std. error = 0.1, Figure 3), indicating that the road erosion rate largely determines the sediment travel distance.

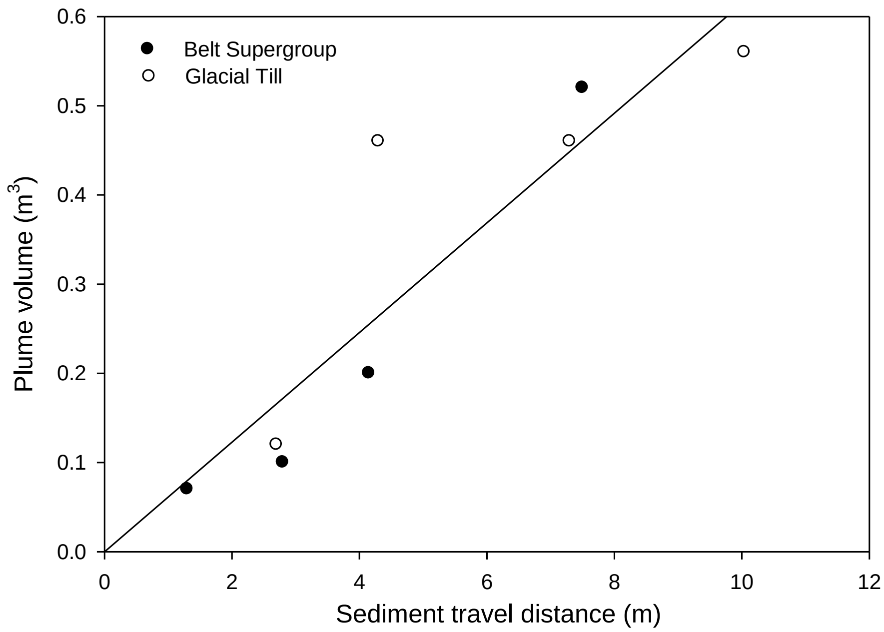

Figure 3. Sediment plume volume versus sediment travel distance for sediment plumes below drivable drain dips in Belt Supergroup and glacial till parent materials. Outlier in Belt Supergroup (Volume = 6.20 m^3, Distance = 7.60 m) omitted from plot.

4.4 Particle Size Analysis

Particle size analysis indicated that there was less clay in the plume sediment sample relative to the road tread sample in four of the five Belt series sites, and the mean clay content in plume and roadbed samples from the Belt Series was significantly different ($P < 0.05$). Three of the five samples taken from the glacial till sediment plumes contained less clay than the road tread sample, but the overall means were not significantly different. The reduction in clay content of the plume samples relative to the road tread in seven of the ten samples collected suggests that fine sediment is being carried beyond the visible extent of the plume.

5. DISCISSION

Previous studies have reported sediment travel distances ranging from zero to almost 200 m, and mean travel distances of between 3.8 and 19.2 m (Table 1). The sediment travel distances measured in the present study are at the lower end of this range, and this is likely due to differences in the parent material characteristics, climate and the type of road drainage structure.

5.1 Effect of Parent Material

The lower mean travel distances in Belt series and glacial till parent materials relative to those in the granitic parent material township and in other comparable studies of sediment travel distances in granitics reflects, in part, the low erodibility of Belt series and glacial till soils in western Montana. These soils contain a high proportion of coarse fragments and this reduces the erodibility of the road surface by creating a natural armoring effect (Sugden and Woods, *in press*). In contrast, granitic parent materials form sandy soils that are inherently vulnerable to erosion.

5.2 Effect of Climate

The relative lack of summer rainfall in western Montana along with the fact that as much as 70% of the precipitation falls as snow, means that annual erosivity is relatively low, and this has the effect of further lowering the erosion rate and the sediment travel distance from roads in all parent materials. For example, roads in glacial till in western Montana produced an average of 5.3 Mg ha^{-1} y^{-1} of sediment over a 3-year period that included both wet and dry years (Sugden and Woods, *in press*). In contrast, roads in glacial outwash in rain-dominated southwest Washington, which receives over 50 inches of rain per year, produced 55-60 Mg ha^{-1} y^{-1} (Bilby *et al*., 1989).

Table 1. Range, mean and standard deviation of sediment travel distances reported in this and previously published studies.

Study	Geology	Location	Range	Mean	Standard Deviation
Present Study	Belt	Drivable dip	0 - 58.2	3.97	6.29
	Till		0 - 33.4	3.19	5.06
	Granitic		0 – 28.7	5.36	6.33
Haupt, 1959	Granitic	Cross ditch	1-112.5	19.27	N/A
Burroughs & King, 1989	Granitic	Culvert	0 - 194.8	38.7	N/A
Ketcheson & Megahan, 1996	Granitic	Fillslope	0.4 – 66.1	3.8	2.6
		Rock drain	1.2 – 33.9	8.7	2.5
Brake et al., 1997	Sandstone / Siltstone	Culvert, road > 5 yr old	0 - 23.2	5.09	4.48
		Culvert, road < 5 yr old	1 - 40.1	9.33	11.37

5.3 Effect of Road Drainage Structure Characteristics

The effect of road drainage structures on sediment travel distance can be assessed by comparing the data obtained from granitic sites in this and other studies. The sediment travel distances observed below drivable drain dips in granitic terrain in the present study are comparable to those obtained for fillslopes by Ketcheson and Megahan (1996) (Table 1).

However they are considerably less than those obtained for rock drains by the same authors, and for culverts by Burroughs and King (1989). Runoff routed to a fillslope or a drainage dip is slowed by vegetation and other hillslope roughness elements. These impediments effectively increase surface roughness and reduce the velocity, leading to deposition before the run-off reaches the hillslope. In addition, the roads included in our study were almost entirely outsloped roads, which distribute flow over a larger area, thus reducing the flow depth and increasing surface roughness and boundary resistance. While isolated areas of "confined" flow occur in the form of minor road tread rilling and/or rutting from vehicular passage, these locations are diffuse across the study area. Additionally, the contributing area to these "channels" is significantly less than the entire road tread as in the insloped road design. In contrast with fillslope outfalls and drivable dips, ditch relief culverts concentrate flow, first in the roadside ditch and then at the outflow point. Additionally, ditch relief culvert outlets, if properly installed, will be placed at the fillslope toe which effectively increases "channel" slope, and hence velocity. Increased velocity at the culvert outlet, generated by increased slope and hydraulic radius, leads to increased travel distance of suspended road sediment.

5.4 Regression Modeling

The only variable to appear in both of the regression models was the road type, reflecting the fact that mainline roads had significantly higher sediment travel distances than spur roads in both parent materials. The higher sediment travel distances along mainline roads are largely due to higher traffic levels and more frequent grading, both of which result in less vegetation cover on the road surface. Vegetation cover serves a number of functions that assist in erosion reduction, principally to reduce raindrop energy and associated soil particle displacement (Wischmeier and Smith, 1958). Vegetation also provides increased surface roughness, which reduces flow velocity, discharge and, hence, stream power. Infiltration capacity also increases as plant roots penetrate the road surface. Finally, given enough vegetative cover and sufficient time, the accumulation of soil organic matter increases the soil water holding capacity so reducing the probability of overland flow during precipitation events.

The length-slope product was identified as a significant predictive variable for sites in the Belt Series. Increasing the road segment length or slope increases the velocity, competence, and stream power of overland flow, leading to an increase in erosion and sediment transport. Brake et al. (1997) also found LS to be a significant predictive variable for sediment transport distance. Luce and Black (1999) found that LS^2 was a better predictor of erosion rates than LS, reflecting the fact that slope has a greater effect on road erosion than segment length.

Hillslope roughness appeared in the predictive equation for sediment travel distances in the Belt Series sites, and has been found to be an important predictor of sediment travel distances in other studies (Haupt, 1959; Packer (1967; Ketcheson and Megahan, 1996; Brake et al., 1997). Roughness elements in contact with the ground surface, be they slash, bunch-grass, regenerative vegetation, etc., serve to impede flow, resulting in run-off ponding, reduced flow velocities, and sediment aggradation, and this leads to reduced sediment travel distances.

5.5 Unexplained Variability in Sediment Transport Distances

The regression coefficients obtained for the models in this study are considerably less than those reported in similar studies, and this may be due in part to differences in the study design and the methods used in data analysis. The regression models developed by Ketcheson and Megahan (1996) explained 70% and 88% of the variability in sediment travel distance below fills and rock drains, respectively, and plume volume was the primary predictive variable. Our study also found that plume volume was highly correlated with sediment travel distance, but it was not measured at all of the sites due to logistical constraints. Inclusion of this variable in our regression model would have substantially increased the model predictive capability. Packer's (1967) model explained 52% of the variability in sediment travel distances. However, one of the characteristics of the regression method is that the strength of the correlation may be artificially inflated by including a large number of variables in the model. This may have been the case with the Packer study, which included 25 variables in the predictive model. Brake et al., (1997) used a stepwise approach that reduces the potential for overparameterization of the regression model, and achieved regression coefficients more than twice as high as those achieved in the present study. Brake et al (1997) used a stratified sampling approach where study sites were replicated within each of three aspects (north, south and east-west), two soil textures (coarse and fine), two USLE length slope coefficients (low and high) and two hillslope gradients (low and high). Such an approach has the advantage of ensuring that all possible combinations of site variables occur in the data set, thus improving the predictive capability.

Other factors that may have contributed to the low predictive capability of the models include variability in erosion rates within parent materials, variable climatic conditions among study sites, the effect of unmeasured variables such as traffic volume, and limitations in the study methodology. The Belt Series includes a wide range of lithologies with corresponding variability in soil texture. In western Montana, most road erosion occurs during spatially isolated but locally intense summer convective storms (Vincent, 1985). Due to the spatially distributed nature of the sampling sites, analogously configured road segments may have been exposed to significantly different precipitation events, resulting in corresponding differences in the sediment travel distance. Variability in travel distances due to different climatic history may be further exacerbated by differences in traffic volume between sites, and by interactions between the timing of vehicle traffic and the occurrence of large storms.

Various factors may have affected the representativeness of the sediment transport distance measurements. Sediment travel distance was measured from the toe of the fillslope so that only sediment plumes that extended beyond the road prism were included in the dataset. The disadvantage of this approach in an environment with steep slopes is that fill slopes can be a significant proportion of the total plume length extending from the edge of the road. In addition, plumes that do not extend beyond the edge of the fillslope are shown as "zero" sediment transport distances in the data set when there is in fact transport of sediment beyond the edge of the road tread.

5.6 Sediment Plume Volume – Distance Relationship

The positive relationship between sediment plume volume and sediment travel distance is logical and was previously described by Megahan and Ketcheson (1996). Sediment diverted from the road surface and onto a hillslope will travel downhill until it is either trapped behind a log, rock or other hillslope roughness element, or until the stream power is reduced sufficiently that the flowing water can no longer convey the sediment load. Downhill extension of the sediment plume over time reflects both the progressive filling-up of hillslope storage and the associated reduction in hillslope roughness along the plume, which leads to a reduction in the rate that stream power decreases below the road. Higher erosion rates lead to more sediment volume on the hillslope, more rapid filling of hillslope storage, reduced hillslope roughness, and longer sediment travel distances. The broader implication is that the road erosion rate is a very important determinant of the sediment travel distance. Road segments with high erosion rates are also likely to have longer sediment travel distances and will thus deliver more sediment to streams, both by direct and indirect flowpaths.

5.7 Management Implications

The generally low sediment travel distances observed in this study indicate that most drivable dips along unpaved roads in western Montana do not deliver sediment to streams. For example, the probability of sediment from drain dips in Belt Series or glacial till parent materials traveling a distance greater than the Montana SMZ width of 15 m (50 ft) is just 5%. Viewed another way, the vast majority of the sediment introduced to streams comes from just a few drainage outfalls. This means that it should be possible to substantially reduce sediment delivery from roads to streams by identifying and treating the relatively small number of drainage outfalls in a watershed that contribute sediment. These outfalls are most likely to occur in the vicinity of stream crossings, where the road crosses into and through the SMZ and the drainage outfall lies just a short distance from the stream. Our study suggests that there is an optimal location for the drainage outfall nearest a stream crossing that minimizes both the direct and indirect sediment inputs to the stream channel. This optimal location may be identified by combining the sediment travel distance probability and plume length – volume relationships presented here with calculated or estimated road erosion rates.

The results of the regression analysis indicate that sediment travel distances may be reduced by increasing hillslope roughness and road vegetative cover and reducing road segment length and slope. On existing roads, hillslope roughness may be increased by installing slash filter windrows or other obstructions below drain dip outflows and ensuring that these objects are in contact with the ground surface. Road vegetative cover can be increased by temporarily or permanently closing roads when they are not being used. Road system designers should avoid constructing long, steep road segments that lead to increased flow velocities and stream power. Since plume length and volume are highly correlated, any activity that increases the road erosion rate will also increase the sediment travel distance. In an associated study, Sugden and Woods (*in press*) identified the road segment slope, time since grading, roadbed gravel content and mean annual precipitation as significant predictors of road erosion rates in Belt Series and glacial till sites. Of these, time since grading is the only variable that can be altered by managers dealing with existing road networks. By grading roads only as needed to eliminate ruts, particularly along road segments near to streams, managers can further reduce sediment delivery and the resultant impact on aquatic resources.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Modeling Runoff and Soil Erosion from an Insloping Forest Road*

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Abstract
Forest roads are essential to display manifold functions of forest by transporting forest products, improving local transportation, and promoting local industries. Soil erosion resulting from forest road construction can be a major cause of non-point sources pollution that adversely affects the physical quality of stream water and aquatic habitat. Eroded materials can also reduce the drainage capacity of road ditches and affect road stability. The main purpose of this study is to predict runoff and surface soil erosion from a forest road using the Kinematic Runoff and Erosion Model (KINEROS2). The KINEROS2 model is an event oriented, physically based model describing the processes of interception, infiltration, surface runoff and erosion from small agricultural watersheds. The KINEROS2 model was calibrated and validated against the observed data collected at two side-ditches of forest road. A total of 7 storm events that occurred in the Yangpyong experimental watershed, Korea, during the period of 1997-1998 were simulated using KINEROS2. The simulation results are satisfactory when compared with the observed hydrographs, and the sediment concentrations during the simulation period. The result shows that the modeling approach can provide valuable information in planning, designing, and maintaining road drainage systems.

1. INTRODUCTION

Forest roads are essential to display manifold functions of forests by transporting forest products, improving local transportation, and promoting local industries. However, soil erosion resulting from forest road construction can be a major cause of non-point sources pollution that adversely affects the health and integrity of the aquatic ecosystem (Fransen et al., 2001). Eroded materials can also reduce the drainage capacity of road ditches, and affect road stability (Dutton et al., 2005).

Forest roads have potential direct effects on hillslope hydrology. It is due to the development of overland flow generated from compacted road surface and the interception of subsurface flow by road cutslopes (La Marche and Lettenmaier, 2001). Concentrated surface runoff, reduced infiltration, and removal of surface cover and roughness by forest road construction can also result in accelerated soil erosion rates and stream sedimentation (Fransen et al., 2001).

Hydrologic and water quality effects by forest road were basically evaluated based on the measurement of runoff and sediment accumulated in depositional locations. While these efforts generated initial estimates of long-term erosion and sediment delivery rates on forest roads, it can be labour-intensive and time consuming process, and do not incorporate field

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 265-271.*

measurements to determine the spatial and temporal variations of runoff and soil losses during individual storm events (Macdonald et al, 2001). Therefore, modeling approaches have been used to investigate how forest roads impact the hydrologic responses and soil erosion processes (Ziegler et al., 2001).

Reid and Dunne (1984) used unit hydrographs and sediment rating curves to describe sediment production rates from forest road surfaces. Ziegler et al. (2001) used KINEROS2 to estimate Horton overland flow and erosion from unpaved mountain roads. Marche and Lettenmaier (2001) evaluated the effects of forest roads on peak flows with a combination of field data and modeling approach in the extensively logged catchment. Dutton et al. (2005) used two numerical models, NUM5 and VS2D, to simulate the effects of forest roads on subsurface flow and slope stability.

The overall objective of this paper is to simulate runoff and sediment production from an insloping forest road, located in the Yangpyung experimental watershed, Korea. A comprehensive monitoring program was conducted in the unpaved roads and corresponding cutslopes. A physically based model, KINEROS2, was selected as the foundation for modeling effort.

2. METHODS

2.1 KINEROS2 Model

KINEROS2 (Smith et al., 1995), the recent version of KINEROS (Woolhiser et al., 1990), is an event oriented, physically based model that has been used as an enginnering tool in the United States and abroad. The model incorporates the processes of interception, infiltration, runoff and erosion to predict runoff and soil erosion from small agricultural and urban watersheds. The watershed is subdivided into cells which represent both planes and channels, in which water and sediment transport are routed. In order to physically describe the water within the model, five categories of inputs are required, such as simulated rainfall information, watershed topography, channel characterization, land cover, and soil parameters (Osborn et al., 1990). Complete documentation for KINEROS2 model can be found on the website http://www.tucson.ars.ag.gov/kineros/ . Brief description of the model is provided below.

When rainfall rate exceeds the infiltration capacity, Hortonian overland flow occurs. Hortonian overland flow simulation in KINEROS2 utilizes the kinematic wave equation to solve the dynamic water balance equation.

$$\frac{\partial h}{\partial t} + \frac{\partial Q}{\partial x} = q(x,t) \qquad (1)$$

where h is the storage of water per unit area, Q is discharge per unit width, t is time, x is the distance along the slope direction, q(x, t) is the lateral inflow rate of surface runoff from surrounding planes and channels.

The mass balance equation is used to represent the movement of eroded soil along a surface flow path for upland erosion.

$$\frac{\partial (AC_S)}{\partial t} + \frac{\partial (QC_S)}{\partial x} - e(x,t) = q_S(x,t) \qquad (2)$$

where A is the cross sectional area of flow, Cs is the sediment concentration, e is the erosion rate in the soil, and q_s is the the lateral sediment inflow for the channels. For upland surface, e is assumed to be composed of the erosion caused by splash of rainfall and the erosion by flowing water.

$$e = e_s + e_h \qquad (3)$$

where e_s is the splash erosion rate and e_h is the hydraulic erosion rate.

Splash erosion rate can be approximated from the relationship

$$e_s = \begin{cases} c_f k(h) rq & q > 0 \\ 0 & q < 0 \end{cases} \qquad (4)$$

where r is rainfall intensity, c_f is a constant related to soil and surface properties, k(h) is a reduction factor dependent upon water depth, and q is excess rainfall.

The hydraulic erosion rate is estimated based on the difference between the current sediment concentration, C_s, and the concentration at equilibrium transport capacity (C_{mx}).

$$e_h = c_g (C_{mx} - C_s) A \qquad (5)$$

where c_g is a transfer rate coefficient. The c_g can be shown to be equal to particle settling velocity (v_s) divided by the hydraulic depth (h) for the condition of deposion, while c_g is less than (v_s/h) for cohesive soils.

Unlike upland erosion, splash erosion is neglected, and the lateral inflow, q_s becomes important for channel erosion simulation. Equation (2) and equation (4) are equally applicable to simulate channel erosion and sediment transport.

2.2 Study Area

The Yangpyong experimental watershed (YEW) is located in the northeastern part of Seoul, Korea (Figure 1). As shown in Figure 1, two plots to measure runoff and sediment yields from unpaved road surface and cutslopes were established in the YEW watershed. Each plot consists of insloped, unpaved road and a cutslope extending up from the inside ditch. At each plot we surveyed road length, road surface gradient, contributing area, and cutslope gradient and height. The detailed descriptions of the plots are summarized in Table 1.

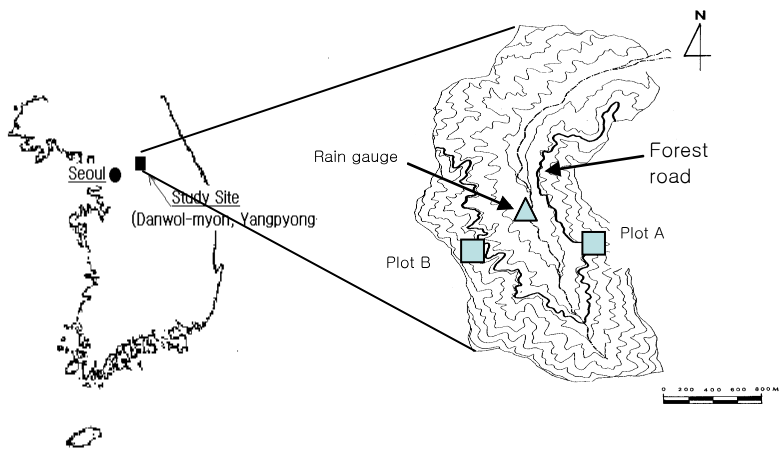


Figure 1. Location of the Yangpyong experimental watershed, Korea

Table 1, Physical characteristics of the selected plots in the YEW

Plot No.	Contributing Area (ha)	Road Length (m)	Road Surface Gradient (%)	Cutslope Gradient (^{o})	Cutslope Height (m)
A	1.06	80	6.0	75	7.6
B	0.82	110	4.0	62	7.0

Rainfall amounts, runoff rates, and sediment yields were measured for each storm. Rainfall was recorded by tipping-bucket rain guage within the watershed (Figure 1).

Runoff data were obtained using surface flow samplers that consist of an intake, a hose, and a storage vessel. The intake is a stainless steel trough with a 60 cm x 20cm rectangular inlet orifice and a 30 cm x 20 cm exit orifice. Water and sediment that enter the orifice flow by gravity, through the outlet, through a flexible connecting hose and into a collecting vessel. The tipping bucket gauge is employed to measure the flow rate in the storage vessel.

2.3 Field Investigation

The experimental plots were operated during the monitoring period (1997 to 1998) representing a wide range of rainfall amounts, antecedent moisture conditions and land cover. A total of 7 storm events were analyzed in this study, as shown in Table 2. Some data were excluded because the rainfall and sediment yield data were considered unreliable. In Table 2, observed runoff volumes and sediment yields for two plots were presented. These values were totals the period of sampler operation.

Table 2. Summary of runoff and sediment yield data measured in the YEW

Storm Events (yymmdd)	Rainfall (mm)	Runoff volume (mm)		Sediment yield (kg)	
		Plot A	Plot B	Plot A	Plot B

S1(970628)	95.5	79.8	61.9	70.19	4.93
S2(970708)	222.0	164.8	209.7	347.81	85.04
S3(970724)	118.0	66.0	72.9	422.79	31.43
S4(970808)	245.0	219.1	174.0	399.96	26.15
S5(070906)	69.0	35.2	41.3	334.75	22.86
S6(980705)	317.0	303.0	250.1	627.29	18.86
S7(980802)	272.0	248.2	182.2	553.22	78.70

The rainfall amounts for these events ranged from 69.0 mm to 317.0 mm, while the corresponding runoff volumes varied 35.2 mm to 303.0 mm at the Plot A. On a per storm basis, the average runoff coefficient for Plot A was 83%, while the coefficient for Plot B was 65%.

Sediment yields from Plot A for the monitoring period ranged from 70.19 kg to 627.29 kg. The Plot A generated 2,756.0 kg of sediment over 7 storms, while Plot B generated 268.0 kg of sediment for the same period. There is a great difference in sediment yields between two plots. On average, Plot A produced 245.5 kg/m^2 per millimeter of runoff, and Plot B had a 32.9 kg/m^2 sediment yield per unit runoff volume.

3. RESULTS

3.1 Hydrologic Simulation

Although KINEROS2 is a physically based model, calibration procedure is needed due to the uncertainty that inevitably in the data sets and the physical abstractions incorporated in the model. Calibration for hydrologic parameters is done by comparing observed and simulated runoff volumes for 7 events in Plot A. The antecedent moisture condition has a significant effect on runoff volume. Therefore, the parameter for antecedent moisture condition (S_i) should be estimated initially to adjust the volume of runoff for each event. Manning's coefficient and soil characteristic data should be calibrated to match runoff volume between observed and simulated data. The calibrated parameters were used for hydrologic simulation in the Plot B for the validation purpose.

Table 3 shows the observed and simulated runoff volumes on the Plot A and Plot B. For the calibration purpose, the overall simulation in the Plot A underpredicted by about 4.8%, compared to observed runoff volumes for 7 events. The relative errors of runoff volumes varied -33.0% at S5 to 18.4% at S7 for the calibration stage. The simulation results indicate that the runoff response from the Plot A was simulated well.

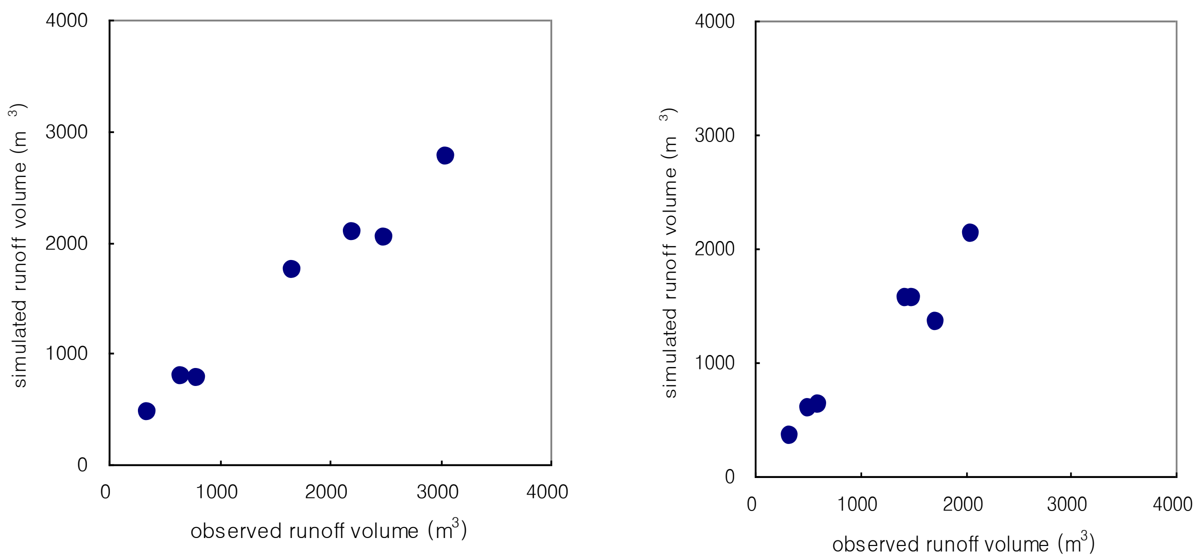
The calibrated parameters were employed for the model validation. The simulated runoff were predicted for 7 events in the Plot B and compared to measure the model performance. The differences between observed and simulated runoff volumes ranged from 21.32% to -17.5% for the validation stage. Table 3 shows that one larger storm (S2) generated an unusually low proportion of runoff volumes in the Plot B. Figure 2 plots the observed and simulated runoff volumes for the calibration and validation stages.

Table 3. Hydrologic simulation results in the YEW

Storm Events (yymmdd)	Calibration (Plot A)			Validation (Plot B)		
	Observed (m^3)	Simulated (m^3)	Error (%)	Observed (m^3)	Simulated (m^3)	Error (%)

S1(970628)	802.8	776.36	3.3	507.6	596.8	-17.5
S2(970708)	1657.9	1749.81	-5.5	1719.5	1352.9	21.32
S3(970724)	664.0	798.74	-20.3	597.8	622.3	-4.1
S4(970808)	2204.2	2093.31	5.0	1426.8	1557.8	-9.2
S5(070906)	354.1	470.92	-33.0	338.7	361.3	-6.7
S6(980705)	3048.18	2761.14	9.4	2050.8	2134.6	-4.1
S7(980802)	2496.89	2037.98	18.4	1494.0	1567.2	-4.9
Total	11228.0	10688.3	4.8	8135.2	8192.8	-0.7

Based on hydrologic simulation, KINEROS2 model tended to predict runoff volumes reasonably well. However, for most storm events in the Plot B, the model tended to overpredict hydrologic response from small watersheds with forest roads.



(a) Calibration stage (b) Validation stage

Figure 2. The comparison of observed and simulated runoff volumes

3.2 Sediment Simulation

Six storm events in the Plot A were selected to calibrate the model parameters. Table 4 presents the observed and simulated sediment yield data for each event in the calibration and validation purposes.

For the calibration period, the model generated an average sediment concentration of about 232.1 kg/l, while the observed concentration is 245.5 kg/l for 7 storm events. The differences in sediment yields between observed and simulated for each storm events ranged 0.3% to 96.5% in the Plot A.

Table 4 shows that the model underpredicted sediment yield in the validation stage. The comparison of sediment yields for the validation stage is also presented in Table 4. The mean values of observed and simulated sediment concentrations in the Plot B were 32.9 kg/l and 157.3 kg/l, respectively.

Table 4. Sediment simulation results in the YEW

Storm Events (yymmdd)	Calibration (Plot A)			Validation (Plot B)		
	Observed (kg/l)	Simulated (kg/l)	Error (%)	Observed (kg/l)	Simulated (kg/l)	Error (%)
S1(970628)	87.4	171.8	-96.5	9.7	154.4	-1490.0
S2(970708)	209.8	177.2	15.6	49.46	146.1	-195.4
S3(970724)	636.8	341.1	46.4	52.58	257.2	-389.3
S4(970808)	181.5	152.4	16.0	18.3	37.8	-106.4
S5(070906)	945.3	948.3	-0.3	67.5	239.9	-255.4
S6(980705)	205.8	168.7	18.0	9.2	131.2	-1326.3
S7(980802)	221.6	261.6	-18.1	52.7	263.8	-400.8
Mean	245.5	232.1	5.5	32.9	157.3	-397.6

4. CONCLUSIONS

Forest road is the major source of sediment that elevates sediment levels in forest streams and adversely impacts stream water quality and aquatic habitat. This study incorporated the measurement of runoff and sediment yields from two experimental plots and a computer model, KINEROS2, to analyze runoff response and erosion process in unpaved roads and surrounding cutslpoes.

Rainfall amounts, runoff volumes, and sediment yields were measures in two experimental plots from 1997 to 1998. The hydrologic and sediment-related parameters were adjusted by comparing the observed and simulated data. The overall difference in runoff volumes for the calibration stage is about 4.8%, while for the validation stage is about 0.7%. The model predicted sediment yield well for the calibration stage, while sediment yields for most storms were underpredicted for the validation. The relative errors of sediment yields for the calibration stage ranged from -95.6% to 46.4%.

Results from this study show that KINEROS 2 model is a useful tool in predicting runoff and sediment yields from insloping forest roads with unpaved road surface and cutslopes. The understanding of runoff and erosion processes obtained in this study can help guide the forest road design, and mitigate the negative impacts of existing forest road

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

The Impacts on Forest Soil of Ground-based Skidding by Manpower During Logging Activities*

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Abstract
Soil attracts attention a component of forest ecosystem with regard to both sustainability and productivity. Extracting activities are one of the most important factors which have influences on distributed forest soil. The extraction system, which is used the most common in mountainous region forests at Turkey (%72), is skidding on ground. Skidding on ground has affected negatively physical and chemical characteristics of soil, fields' productivity and sustainable vegetation generation.
In this study, it was investigated spruce (Picea orientalis) forest growing on steep slopes and different lands (North and South) in Northeastern Turkey. This study evaluated the effects of ground-based timber skidding some physical and chemical properties (pH, soil compaction, bulk density, water holding capacity) of forest soil. Measures related to soil properties were analyzed soil samples which taken from soil depths (0–20 cm and 20–50 cm) in pre- and post-harvest. In this study, 96 soil samples were analyzed.
The effects of timber skidding activities are often characterized by significant changes in surface soil properties. It was determined that the most changing were in 0–20 cm soil depths.

Keywords: harvesting impacts, skidding, soil compaction, bulk density, pH, water holding capacity,

1. INTRODUCTION

The forest which is uncovered nature conditions is dependent to soil and a restorable source. State of forest enterprise not only wood raw material production but also include in services as biological diversity, water resources, recreation and wild life. The most important component of forest ecosystem from the point of view of both sustainability and productivity is forest soil. Forest soil disruption is in the first raw at "effective signs during choose of wood raw material production systems" topics which were determined by FAO (1987). This situation has brought up how much the important of soil damage.

The positive and negative effects of interferences on forest ecosystem affect all sources in basin. Therefore to protection natural balance among forest ecosystem components is necessary for both carry on forest presence and sustainability benefit from forests.

Approximately 46% of forest area in Turkey is on steep land. The most common applied timber extracting method (over %72) in these forest lands is ground-based skidding by manpower (Acar et al., 2005). Although alternative harvest systems as skyline and helicopter

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 283-290.*

yarding, cause less soil disturbance, but these techniques are generally more expensive than ground skidding on all. But, ground-based extraction systems are likely to continue to be important in spite of their negative impacts on soils. Skidding resulted in soil compaction, displacement of surface mineral soil, loss of organic matter, and loss of nitrogen, an essential nutrient.

Soil disturbance is a natural consequence of timber harvest. Conventional logging methods as ground-based skidding method have serious effects for sustainability benefit from forest sources. These operations have caused to compaction among different soil layers and to disturbance on soil. These affect negatively both physical and chemical characteristics of forest soil and nutrient including.

Direct effects of skidding on soil's physical and chemical features are as soil compaction, moving of organic matter, bulk density, water holding capacity, porosity, root growth, drainage, aired and soil microorganisms activities (Bozic, 2003; Jurgensen et al., 1997). Indirect effects of skidding on soil's physical and chemical features are reducing of plant growth because of hindered seed germination, restriction soil-water retention in rainy periods because of slippery skidding lines and flowing of seeds by means of rain (Pinard et al., 1996, Ebisemiju, 1990).

The aim of this study is to examine the impacts of skidding on some physical and chemical features (soil compaction, bulk density, water holding capacity and pH) of forest soil which different soil levels (0-20 cm and 20-50 cm), and comparison to pre-harvest and post-harvest reasons.

1.1. Literature Summary

Forest operations such as timber harvesting, ground based skidding, road construction and recreation have the potential damages on forest soil. Johns et al. (1996) showed that 50-54% of the effects of logging on ground surface at a site in the eastern Amazon were related to timber extraction.

Soil compaction has been occurred during timber harvesting is the biggest problem which may rise in the future as a result of increasing a number of skidded timbers (Langmaack et al., 2002). Besides soil compaction typically alters soil structure and hydrology by increasing bulk density, breaking down aggregates, decreasing porosity, aeration and infiltration capacity and by increasing soil strength, water runoff, erosion and water logging (Grigal, 2000; Startsev and McNabb, 2000). The effects of soil compaction can persist in a forest soil for several decades depending on soil texture, skidding activities, soil moisture content, and other soil conditions at the time of harvesting (Corns, 1988).

Landsberg et al. (2003) examined soil compaction post-skidding wood raw material in mixed conifer forests. They determined that average soil compaction was 500 kPa over. Besides it was designated that dried soil assisted in increased soil compaction after timber harvesting activities. Besides, Ares et al. (2005) told soil bulk density at the 0-30 cm depth increased from 0,63-0,82 Mg m–3. Soil strength in skidding lanes increased at all depths <55 cm but never exceeded 1300 kPa. Total soil porosity decreased 10-13% with compaction, while available water holding capacity increased.

Laffan (2001) compared soil features of undisturbed and harvested areas. He determined that bulk density was 20% more at top soil cover (0-10 cm) in harvested areas. Tan et al. (2005) found that soil compaction increased mineral soil bulk density by an average of 24%, reduced aeration porosity by as much as 50%, and lowered growing season soil temperature and moisture content.

Demir et al. (2005) investigated some changes in the forest soil characteristics at 0-10 cm depths. They found that bulk density values to be quite high in the samples taken from the skid road, also the porosity and moisture equivalent values decreased extensively. Moreover the soil acidity values (pH) were shown significant differences soil samples taken from skid road and undisturbed area.

Shetron et al. (1988) determined significant differences in the 0-5 cm surface soil density occurred only between undisturbed and skid trail. Also they explained bulk densities in the surface layer were increased by about 85% as a result of skidding.

2. MATERIAL AND METHOD

2.1. Study Areas

The study was conducted at Trabzon province in northeastern Turkey at approximately 390 39'-390 45' East longitudes and 400 45'-400 52' North latitudes (Fig. 1). The essential forest tree of this region is Picea orientalis. Besides there are partly Rhododendrons subs. (R. tulipifera, R. ponticum) at North slopes.

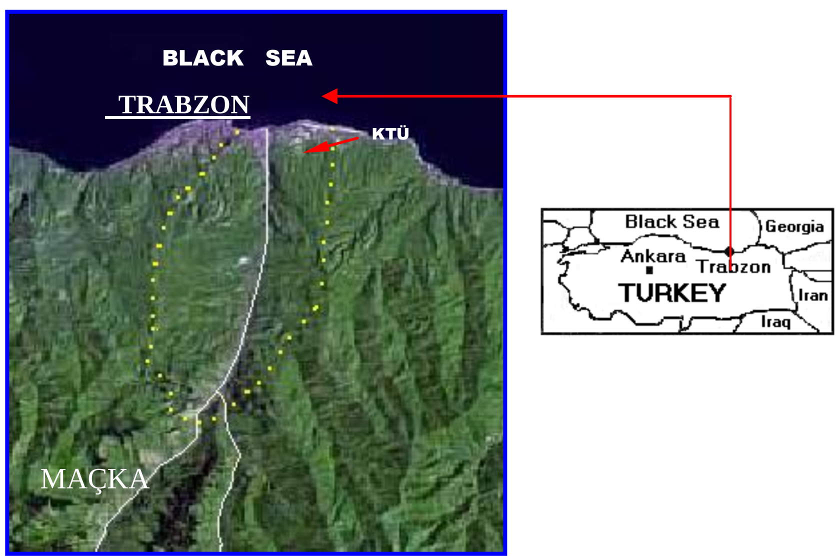

Figure 1. The location of researched areas in Trabzon Region

Average field elevation is 850 m above sea level, average slope is 70% percent, and essential aspects are North and South. Annual mean temperature is 14oC, and the highest (38.2oC) and the lowest (-7oC) temperatures have occurred in July and January respectively. Average annual precipitation is 731.6 mm, and the highest and the lowest precipitations have occurred on April-May and October-December months respectively (Anonymous, 2002).

Tree harvesting, branch trimming and classifying activities were done by motor-saw, and skinning was done by ax in the study areas. Wood raw material transportation works were being carried out ground based skidding by manpower without whatever helper tool.
It was used to a digital camera to televise study areas, GPS and klizimeter to determine geographical features, digging tools to engrave soil profile and take soil samples, iron cylinders and wooden sledgehammer needed to bulk density and permeability analyzes.

2.2. Soil Sample and Datum Collecting Methods.

It was determined total 16 units experiment areas, which are 20 m X 20 m dimension, to compare to pre- and post-harvest soil characterizes. In the experiment areas, total 48 soil profiles were engraved and collected total 96 units soil sample from the mineral soil layer to different two soil depths (0-20 cm and 20-50 cm). Also it was collected total 48 units cylinder sample in each soil profile to determine bulk density parameter. Taken soil and cylinder samples were settled to nylon bag and labeled. Soil compaction at the places where forest floor samples were taken was measured by using a penetrometer. Measurements were performed down to 20 cm depth, as a 0–20 depth range is usually used in the literature (Servadio et al., 2001; Brevik et al., 2002) and because it avoided the natural compaction beginning at 40 cm depth.

2.3. Laboratory Analyses

All extractions were done with in 1 week of sample collection. Composite soil samples were air-dried, sieved with a 2 mm screen and thoroughly mixed before analyses were carried out. Afterwards soil samples were analyzed and determined pH, bulk density and water holding capacity parameters.

Sample collected in cores for bulk density were oven-dried to constant weight at 105°C. Soil bulk density was calculated based on the volume of the soil core and oven-dry soil mass. pH was measured in H,O and 0.1 M KC1 (soil: solution ratio 1:2.5) with a Orion 420 A digital pH meter. Water holding capacity was analyzed by soil cylinder samples (Özyuvacı, 1978).

2.4. Statistical Analyses

The SPSS 11.5 package program was used to perform all statistical analyses. It was produced mean, standard deviation and standard error mean of soil characteristics (pH, bulk density, water holding capacity and soil compaction), which had determined in pre- and post-harvest. Statistical significance was accepted at 0.05 for all statistical analyses. Relationships between pre- and post- harvest soil parameters were compared to by paired sample test (Table 1) (Özdamar, 2002).

3. RESULTS AND DISCUSSION

In this study, it was examined the impacts of ground based skidding on some physical and chemical features of forest soil and compared to pre- and post-harvest soil parameters. It was produced that physical and chemical characteristics of forest soil in both soil depths (0–20 cm and 20–50 cm) had negatively affected because of skidding activities. It was determined that soil compaction, bulk density and pH increased and water holding capacity decreased after skidding activities. Mean, standard deviation and standard error mean of these soil features are given in Table 1.

Table 1. Mean standard deviation and standard error mean of investigated soil features

Soil Depths			Mean	Std. Deviation	Std. Error Mean
0-20 cm	Pair 1	Post-Harvest pH	5,8129	,74827	,15274
		Pre-Harvest pH	5,9804	,90116	,18395
	Pair 2	Post-Harvest Water Holding	36,3133	6,79024	1,38605
		Pre-Harvest Water Holding	41,3258	8,64523	1,76470
	Pair 3	Post-Harvest Bulk Density	,8229	,11495	,02346
		Pre-Harvest Bulk Density	,7717	,10909	,02227
20-50 cm	Pair 1	Post-Harvest pH	6,0829	,78162	,15955
		Pre-Harvest pH	6,4004	,71614	,14618
	Pair 2	Post-Harvest Water Holding	28,7000	6,09233	1,24359
		Pre-Harvest Water Holding	33,1313	7,88499	1,60952
	Pair 3	Post-Harvest Bulk Density	1,0171	,08966	,01830
		Pre-Harvest Bulk Density	,9083	,13011	,02656

In this study, after ground based skidding activities, soil compaction increased in from 86 kP to 127 kP. Soil compaction is perceived as one of the leading causes of soil degradation resulting from forest operations (Brais, 2001). Difference between soil compaction values in pre- and post-harvest can be originated from skidding distance, a number and size of log extracted and land slope.

In the pre- and post- harvest soil characteristics in both soil depths compare statistically by paired samples test. It was determined that differences only water holding capacity in the top soils and in the sub soils among pH, water holding capacity and bulk density characteristics (Table 2).

Table 2. Relation to among soil features in pre- and post harvest

Soil Depth (cm)		Paired Differences			t	Sig. (2-tailed)	
		Mean	Std. Devia.	Std. Error Mean			
0–20	Pre-Harvest -pH & Post-Harvest -pH	-,167	1,235	,252	-,664	,513	NS
	Pre-Harvest -Water Holding & Post-Harvest -Water Holding	-5,01	9,750	1,990	-2,519	,019	*
	Pre-Harvest -Bulk Density & Post-Harvest -Bulk Density	,051	,160	,033	1,565	,131	NS
20–50	Pre-Harvest-pH & Post-Harvest-pH	,317	,720	,1470	2,159	,041	*
	Pre-Harvest -Water Holding & Post-Harvest -Water Holding	-4,43	9,406	1,920	-2,308	,030	*
	Pre-Harvest -Bulk Density & Post-Harvest -Bulk Density	,109	,1673	,0341	3,185	,004	*

Significance levels are NS non-significant, * 0.05 >, values within columns followed by the same letter are not statistically different at 0.05 significance level.

It was determined harvested forest area with significant change in bulk density in any soil horizons (0–30 cm) soil (Pennington, 2004). In the same way, this study exposed bulk density was increased by soil compaction in both soil depths (0–20 cm and 20–50 cm) are 8% and 12% respectively. Therefore, increasing in bulk density was partly brought about by the exposure of denser subsoil. The increases in bulk density observed in this study were lower than those reported in the above works, but this may be associated to factors such as soil type, magnitude of soil disturbance or amount of timber removed.

It is accepted that bulk density which plant roots can not penetrate considered as the critical level is between 1,40 and 1,55 g cm-3 (Daddow et al., 1983; Kozlowski, 1999) at soils with light and medium texture, and 1,46 g cm-3 at soils with fine texture (Craul, 1992). In compacted plots, the most bulk density value was determined 1,20 g cm-3. These values did not exceed the critical values. Because of the soil compaction that occurred on forest soil after skidding, water holding capacity decreased about 12,5%.

Soil acidity values increased about 6% at both soil depths. Organic matter has an important effect on the soil acidity. During ground based skidding organic matter can be moved, and surface flows can be occurred because of sedimentation are effective on the soil acidity. Increased pH can come true related to carrying organic matter and increased evaporation from soil.

Soil compaction caused to decrease pH and water holding capacity, and increase in bulk density. These disturbances to physical and chemical features of forest soil can be related to skidded in summer, volume of skidded timbers, ground based skidding by manpower without whatever helper tool and worked untrained workers.

In order to negative alteration of soil features, it will be suitable for making skidding activities in dry season, which soil moisture is low, or in winter. In this way, both road care expenses and soil damage will be prevented.

Holota (2005) emphasized that constant skid roads in forest minimizes skidding damages in stands. Because there are not skid roads in study areas, skidding activities was done at randomly. The random skidding brought about disturbed soil extensively.

4. CONCLUSIONS AND RECOMMENDATIONS

In this study, it was assessed the impacts of ground-based skidding by manpower on some physical and chemical properties (soil compaction, bulk density, water holding capacity and pH) of forest soil in different soil levels (0-20 cm and 20-50 cm), and comparison to pre-harvest and post-harvest reasons.

Ground based skidding activities modified some physical and chemical properties of soil which are important to soil productivity and conservation. Soil properties and forest productivity can be affected by skidding activities but these impacts vary greatly with site conditions and operational practices.

It is impossible to skidding of wood raw material on forest floor without disturbed soil. Forest soil disturbance has changed committed to a lot of factors as majority and severity of production, soil features, and soil moisture content at the time logging, topography and extracting method.

Because research areas are very steep and rough, various disturbs were occurred as a result of hitting, hipped on soil and pressure of timber on forest soil during skidding. Soil compaction, which is the most important result of skidding, is one of the most essential reasons of soil disturb occurred as a result of forest harvesting activities. Prohibiting wet-weather skidding and skidding on steep slopes further reduces soil disturbance.

Soil compaction, bulk density and water holding capacity features have leaded to a lot of physical and chemical activities effective to assessed sustainability and productivity of forest ecosystem. This study showed that ground based skidding affected to especially water holding capacity and pH from soil features. Pre-harvest planning increases the efficiency of log extraction and reduces the area disturbed. To reduce soil disturb, it is established well-planned skidding road networks in forests. In this way, timber will be reachable in steep area, where wood raw material is skidded by manpower, reducing disturbed land by skidding and soil damage severity.

Most of forest workers are untrained about logging activities. Therefore education level of forest workers affect to productivity levels of work labor, forestry it is necessary an education will improve to environs conscious for forest workers because of productive and sustainable.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Environmental Performance Measures for Forest Roads*

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Abstract
Best Management Practices (BMP's) for forest roads have evolved over the last 35 years, since adoption of Oregon's Forest Practices Act (the first in the United States). Oregon's BMP's are objective based, not prescription based, recognizing that one prescription can never fit all situations. To determine how well environmental protection objectives are met, performance measures for roads are needed. A rapid field survey was developed and is being used to determine current condition and environmental risk factors of roads at a watershed scale on State Forests. Information from this survey is used to evaluate at least six environmental performance indicators: 1) road location in relation to streams or landslide/other serious erosion prone slopes; 2) stream crossing effects on fish passage; 3) washout and diversion risk at stream crossings; 4) percent of road system with hydrologic connection to streams; 5) land area dedicated to roads and not growing forests; and 6) the general condition of the prism, surface, drainage system, and brush/weeds. This information can be used to prioritize road work and help compare different roads systems and help evaluate if more or less road work is needed overall.

1. BEST MANAGEMENT PRACTICES

There is a large body of research showing roads (including forest roads) can have negative impacts on the environment, especially on water resources. Some of this research dates to the mid 1940's (Leiberman and Hoover, 1948; Brown and Kryger, 1971). Based in part on this research, Oregon was the first State to develop a Forest Practices Act in 1971, with rules adopted in 1972. Road location, construction and maintenance are important elements of these rules. Research and monitoring on the effects of different road design and construction practices accelerated after the initial rules were adopted, and as a result, major revisions to the road rules occurred in 1978, 1983, 1994, and 2002. The most recent changes occurred five years after the State and private landowners implemented a *road hazard identification and risk reduction project*.

The author has over 24 years experience in developing, implementing and monitoring road location, design, construction and maintenance practices in multiple geologies, climates and land managers objectives across Oregon. This included following development of forest road BMP's in other western States and Provinces. While BMP's are similar in these authorities, they are applied differently and there are few widely accepted measures of specific environmental effects of roads or practical metrics for these effects. As a result, grossly simplistic metrics like road density have sometimes been used. Experience and monitoring data show that simple, objective practices like good road location, getting away from steep slopes and streams, works. On the other hand, even very good design through tough areas is less certain to result in a low

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 291-300.*

risk road. (Dent and others, 2003; Robison and others, 1999). This paper includes metrics that can be compared within and between regions to determine the relative risk of different road systems.

Objective practices: Since their inception, Oregon's Best Management Practices (BMP's) for roads have been objective based, rather than prescription based. Objective based BMP's have a resource protection objective and allow multiple options for achieving the objective. Two examples (Oregon Administrative Rules - OAR's) follow:

OAR 629-625-0310 Road Prism (1) *Operators shall use variable grades and alignments to avoid less suitable terrain so that the road prism is the least disturbing to protected resources, avoids steep sidehill areas, wet areas and potentially unstable areas as safe, effective vehicle use requirements allow.*

OAR 629-625-0330 Drainage (1) *The purpose of this rule is to provide a drainage system on new and reconstructed roads that minimizes alteration of stream channels and the risk of sediment delivery to waters of the state....*

Prescriptive practices: The alternative to objective practices are prescriptive practices. Prescriptive practices describe precisely where and how BMP's are to be applied, with little flexibility for alternative practices. Prescriptive practices seldom apply to all situations, and sometimes do not treat the major environmental risks. Examples include:

- Maximum allowable road density
- Rigid cross drain (culvert or waterbar) spacing, usually based on road grade
- Complete seasonal haul restrictions by rain or period
- No roads on high landslide hazard locations (formerly high risk sites)
- All stream crossing structures must be designed for a 100 year flow

1.1 Environmental risks of forest roads

The principal effects of roads on streams and aquatic habitat include:

1. Restriction of fish, flow, sediment and debris passage at stream crossing structures;
2. Input of sediment in amounts over background;
3. Alteration of aquatic habitat from sediment, increased fines in stream sediment, and, for roads adjacent to streams, directly filling and eliminating habitat;
4. Change in hydrology and stream flow when roads intercept rainfall and groundwater and alter rate of water delivery to streams

Proper BMP application can greatly reduce and sometimes eliminate these environmental effects. However, most BMP's are designed for site specific application while environmental effects are more often related to the accumulation of conditions and risks at a watershed or landscape level. For example, across the landscape there are usually many road segments with very low resource risk, and fewer road segments with much higher risk. A few roads that do not comply with BMP's may not be that important in the larger picture, especially if those roads are not near streams or in landslide prone terrain. On the other hand, an entire road system on steep, landslide prone slopes, even when constructed with all BMP's can pose significant risk to water resources. And a single very high hazard site (like a high fill with a puncheon) can fail as a dam break flood and cause significant damage to the aquatic environment.

There has been no systematic process for evaluating environmental effects with widespread acceptance in the forestry community. Measuring sediment on a road system scale is really not feasible. Most research has occurred on a very small scale (from road to single ditch and culvert). The most widely (mis)used metric, road density, assumes all road risks are equal and taken to the extreme, this metric considers an interstate highway with a 300 foot right of way built in a river canyon the same as a 14 foot wide forest road on a ridgetop. We know this not to be the case, if it were there would be no reason for BMP's. Research shows a tremendous difference in landslides and washouts between old salvage roads and roads that are newer or have been upgraded to current standards (Robison and others, 1999). As for road density, in the western U.S. roads are quite narrow, and it takes a high road density to disturb much of the forest. A better metric is roads in "critical locations" as described later.

Ideal road: From an environmental perspective, a "good" road stabilizes rapidly, has low connection to streams, passes fish and water at stream crossings with low risk of major damage in flood, is just wide enough for the intended use, and is on the gentlest slope available. It also reaches the best landing locations. From a regulator's perspective, it should efficiently minimize or eliminate chronic sediment delivery to streams and not pose a long term risk of direct channel alteration, washout, fish blockage, or landslides. The Forest Engineer needs to do this at minimum cost, plus have the grade and alignment needed for log truck use, and also keep water from weakening the road prism and surface.

The most expensive locations for road construction are steep slopes and crossings of fish bearing streams. Objective BMP's require site evaluation, assessment and analysis to balance environmental protection with minimum cost. End-hauling is very costly, and there is not a lot of information on alternative practices like spreading out sidecast and ensuring effective drainage. A comparison between forest and public roads may indicate that resources should be spend on the public roads first, where single crossings sometimes block many miles of adult fish passage. Providing juvenile passage is expensive on steep gradient streams, and if there is little (or any) habitat accessed this may not be cost effective. Using a culvert width that matches the active channel width and is imbedded (sometimes seeded) is an effective and reasonable economical (compared to a bridge) for both adult and, where needed, juvenile passage.

1. 2 Road environmental hazards survey development in Oregon

In the late 1990's, a number of west coast salmon stocks were proposed for listing, or actually listed under the Endangered Species Act. In response, Oregon's governor called for an Oregon Plan for Salmon and Watersheds. This plan included a Road Hazard Identification and Risk Reduction Project (voluntary, sort of). This author worked with a group of private landowner engineers to develop a road survey (under short time constraints). This survey was general, so landowners could make fit their individual needs. It was designed to help determine repair priorities at a time when GIS and GPS tools were far from robust. When this original survey was developed, we assumed analysis methods would be fairly simple to develop. This proved to be an incorrect assumption. We have since learned that analysis by the inspector on site is superior to post data collection analysis, at least in many cases. Of note, this project called for monitoring to occur in the year 2007. Because of the inability to organize and analyze data from the original survey, the current condition and watershed risk survey described in this paper was developed and implemented on several watersheds.

1.3 Environmental risk components and performance measures

Environmental risks are both short term (chronic) and long-term (episodic, usually related to major storms). These have been broken into functional components (parts, structures or systems along a road). Each is measured during the road survey, most as begin and end points (segments) when conditions change, with points used for stream crossings. The risk factors associated with roads in mountainous terrain follow:

1. Road location in relation to streams or landslide/other serious erosion prone slopes;
2. Stream crossing effects on fish passage;
3. Washout and diversion risk at stream crossings;
4. Percent of road system with hydrologic connection to streams;
5. Land area dedicated to roads and not growing forests; and
6. General condition rating of the prism, surface, drainage system, and brush/weeds.

Each of these components are described below, concluding with achievable targets (at least for the Pacific Northwest).

Road location risk: Road location has a big influence on the long term risk of the roads. In Oregon, *critical locations* have been defined by the Oregon Board of Forestry policy for implementing existing rules. These are locations, where BMP's are only partially effective. They are sorted by stream-associated, slope-associated, and non critical. In order of risk, from high to low, the stream related are: *canyon fill; channel fill; stream in ditch; stream parallel; and wetland* and the slope related are: *cut and fill slides; fill slides; deep active slides; steep fill; deep inactive slides and steep full-bench.* A road with some channel fill and stream parallel conditions is shown in figure 1. In other regions, *decomposed granite* (above some slope threshold) and *inner gorges* would also be considered critical locations. *Non-critical* locations (where there is little or no risk when BMP's are applied) make up the large majority of most road systems.

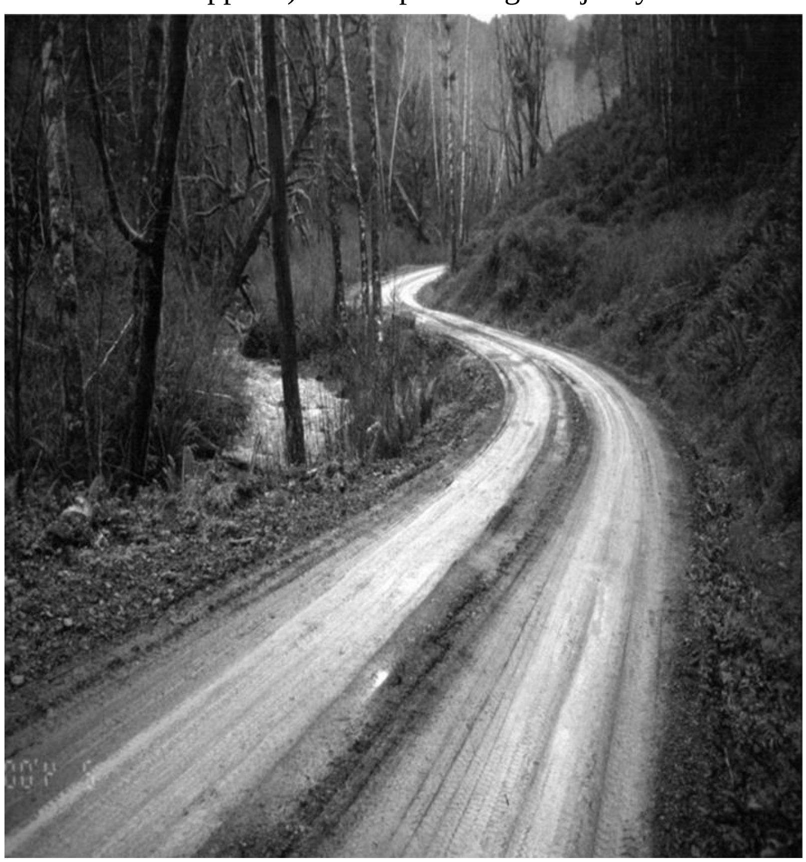

Figure 1. Critical Location Example -Stream Parallel Road (In The Riparian Area And Filling Portion Of Stream Channel)

Roads in critical locations pose long term risks, usually for the life of the road (or beyond). This risk can be reduced but not eliminated. There are specific criteria for each of these risk categories. Training is required for proper categorization, it appears that a roads specialist or skilled forester can be trained in 3 to 5 days. Depending on age of the road system, and the steepness of the slopes in the watershed, we have found between 5 and 37 percent of road systems in critical locations (most of these are located in the lower risk stream parallel or steep fill categories).

Table 1. Critical Locations in the Wilson River Watershed (as a percent of the open road system)

		Watershed		
Critical Location Risk	**Risk**	**Wilson -open**	**Nehalem**	**Miami**
Stream Related				
Canyon fill	Highest	0.1	0	4.7
Channel fill	Highest	0.3	0	6.1
Stream in ditch	Highest	0.1	0.01	0.1
Wetland	Highest	0	0.03	0
Stream parallel	Moderate	7.0	4.1	4.0
Slope Related				
Cut and fill slides	Highest	0.3	.02	0.6
Deep active slide	Highest	0.1	0	0
Fill slide	Highest	0.9	0.03	4.1
Steep fill	Moderate	11.4	1.2	15.0
Full bench	Moderate	0	0.2	2.4
Non critical	Negligible	80.2	94.4	63
Hydrologic Connection	--	15	16	20

Fish Passage at Stream Crossings: It has long been recognized that salmon must migrate upstream to spawn, and excess drops with inadequate jumping pools, or very high stream velocity can prevent the migration of adult fish. More recently, the passage of juvenile fish has been recognized as of high importance for additional habitat and fish safety. Juvenile salmon and non-migratory trout often live in small streams, sometimes with steep gradients. In the past, these streams had been thought to be unimportant for fish, so often were not surveyed for fish. Culverts can easily be barriers to upstream fish migration, especially for juvenile fish. As a result, bridges and natural channel simulation culverts are now commonly installed. This survey evaluates each stream as *known*, *likely*, *possible*, or *no* fish use based on direct observation, prior fish surveys, or active channel width and stream gradient above the crossing. If fish presence is possible or more likely, the crossing is rated for fish passage as *full passage*, *juvenile barrier* or *adult barrier* based on the outlet drop and the condition (gradient and substrate) at the bottom of the culvert.

Improvement of fish passage has been a priority for Oregon's State Forests, with many re-installations over the last ten years. Larger streams with lower gradient are likely to have the greatest environmental benefit from fish passage improvement. In known fish-bearing streams, we have found less that one percent of our stream crossings are barriers to adult fish, and less than 5 percent are barriers to juvenile fish. We find a number of unknown barriers in likely or possible fish use streams. These are priority locations for fish presence surveys. It is important to evaluate streams around potential juvenile barriers in detail, as natural barriers may make attempts to provide juvenile passage unsuccessful. It should be obvious (but not always is) that fish passage is needed only where and when it would occur naturally.

Washout and diversion risk at stream crossings: Culverts are designed for peak water flows, but not for the unknown sediment and wood contained in these peak flows. Despite this, failures of stream crossings have been uncommon, even in the storms of 1996 (Robison and others, 1999), in parts of the north coast of Oregon the storm of record. Washouts usually occur when the fill is overtopped, and behave as a small dam break flood with effects similar to debris-flows. Diversion occurs when at least a portion of the flood flow runs down the road, causing severe gullies and often a cascade of drainage structures down the road. Since debris can plug any culvert, damage may not be well correlated with design flow of the culvert. Therefore, looking at only peak flow capacity is not the best metric of potential catastrophic sediment input. In addition to the culvert capacity, the height of the fill, fill material, and whether the road climbs through the stream crossing without a overflow dip are all as important as design flow. Smaller culverts in wide valleys with overflows (sometimes called vented fords) have a culvert that usually passes less than a five- year flow through the pipe, but when properly constructed pose low risk to aquatic resources.

This is therefore a fairly subjective measure of risk. Each stream crossing is rated as low, moderate or high risk, or as washed-out. High risk is reserved for high fills with older or small culverts, or where a long grade climbs through the stream crossing without a means for overflow. For new road systems in moderate sloped terrain, less than 1 percent of crossings have high washout/diversion risk. An older road system in steep slope areas can contain 9 percent (open roads) to as high as 15 percent (closed roads***)*** with high washout/diversion risk.

Percent of road system with hydrologic connection to streams: *Hydrologic connectivity* to streams is now a now becoming a measure of road system environmental effects in western North America. Hydrologic connectivity exists when water intercepted by the road prism is routed directly to streams, rather than to an area where drainage waters will re-infiltrate into soils. A lower value is better. Undisturbed forest soils in many areas (including most of Oregon) are extremely porous (high infiltration rates), and design standards have changed to direct as much drainage onto these porous soils and away from direct entry to streams as possible. Hydrologic connection may be by ditch, gully or overland flow and values of 57 percent to as high as 75 percent stream have been reported in older studies (Wemple and others, 1997; Reid and Dune; 1984). More recently designed or improved roads have a hydrologic connectivity between 15 and 34 percent (Dent, and others, 2003; Bilby and others, 1989**)**. Without hydrologic connectivity, eroded sediment carried in drainage water cannot flow to streams.

Hydrologic connectivity is determined by evaluating the condition at each cross drain and stream crossing structure. If the discharge is within 50 feet of a stream, it is almost always considered connected, as is any cross drain with a gully that extends below the outlet. ODF surveyed roads average under 20 percent connectivity, in most cases around 15 percent. This is much lower than past studies, and shows it is possible to get water away from the road and minimize drainage discharge into creeks. **The more disconnected the road system, the better our argument to keep roads as a non-point source instead of a point source.** This author's opinion is that hydrologic disconnection will keep most surface eroded sediment out of streams, and it's a lot cheaper than other fixes.

Land area dedicated to roads: The subgrade and cutslope of roads support little or no growth, while a fill can have similar productivity to the surrounding forest. Determination of these parameters requires occasional measurement along the road, and long segments of road are normally lumped together. We find average subgrade width is 19 feet and average cutslope width is 6 feet. When multiplied by length, this indicates 2 to 2.5 percent of Oregon State Forest land is road. The actual effect on forest productivity may be less, since trees use some of road opening on edges. However, if right of way brushing is wide, the effect will be greater.

Current Condition: This survey rates the a) prism, b) drainage system, c) surface, and d) vegetation affecting road use, as well as the all stream crossing structures and cross drain culverts. Each is rated from 1 to 5. A rating of 1 indicates very poor condition and a rating of 5 indicates perfect condition, as shown in Figure 2**.** Ratings change as conditions change along the road, though if conditions are good the rule is to lump rather than to split. The current condition categories are indicators of recent maintenance and repair of the road system, and are indicators of short-term risk to streams. Table 2 summarizes actual ratings for all the ODF roads in the Wilson River watershed (the most recently surveyed).

Code 1 blocks the road, prevents drainage, makes the road unsafe to use, or otherwise is causing road damage and/or serious erosion that affects water quality. Road work is required immediately if the issue affects water quality or the road is not intentionally closed.

Code 2 significantly restricts road use, or the ability of water to drain across the road, and if left alone will likely get worse over time.

Code 3 has a moderate effect on road use, speed, or water flow across the road, but is not an imminent forest practices problem and though it may reduce driving speed, is not a serious safety hazard. Code 3 conditions need maintenance or repair in the future (next few years for inactive roads, sooner for active logging roads).

Code 4 is a minor impairment in function that does not require immediate maintenance or repair.

Code 5 indicates perfect working order and there is no effect on the road function as designed nor is there increased erosion.

Figure 2. Road Attention Priority Code Descriptions

Table 2. Attention Priority Codes Summary for Open Roads Surveyed in the Wilson River Watershed

Open Roads

Linear features

Condition	AP Code 1	AP Code 2	AP Code 3	AP Code 4	AP Code 5	Total Miles
Brush	0.0	6.3	48.7	218.3	154.8	430.0
Drainage	0.1	2.4	26.1	241.1	59.0	430.0
Prism	0.1	3.2	42.4	265.3	119.3	430.0
Surface	0.3	38.8	115.8	267.6	7.5	430.0

Points

Type	AP Code 1	AP Code 2	AP Code 3	AP Code 4	AP Code 5	Total # Surveyed
X-drain culverts	9	79	382	1339	505	2314
Stream Crossings	3	18	72	391	184	668

Closed Roads

Linear features

Condition	AP Code 1	AP Code 2	AP Code 3	AP Code 4	AP Code 5	Total Miles
Brush	49.7	33.2	34.4	24.6	4.6	146.0
Drainage	3.1	5.5	23.0	103.1	11.9	146.0
Prism	6.8	6.9	17.7	82.8	31.9	146.0
Surface	46.7	57.6	28.0	12.9	0.9	146.0

Points

Type	AP Code 1	AP Code 2	AP Code 3	AP Code 4	AP Code 5	Total # Surveyed
X-drain culverts	14	21	34	106	20	195
Stream Crossings	44	32	44	102	37	259

2. ROAD SYSTEM ASSESMENT

At the present time, most of the analysis is visual, looking at GIS maps and also based on comparisons between different road systems. Overall, the survey indicates that our current road system is in excellent condition, if anything indicating in some areas we may not need as much maintenance as under current practice, and road improvements have reduced road risk. The percent of road system with hydrologic connection to streams is low (15 to 20 percent) compared to 34 percent prior to the *Road Hazard Identification and Risk Reduction Project.* Immediately after adoption of the 1994 fish passage rules, only 60 to 75 percent of new culverts were installed properly for fish passage, now that number is over 90 and in some cases approaching 100 percent. Results are depicted in both tabular and geographic (GIS) format. **Note that the GIS displays are best analyzed in color and at larger scale than reasonable for this paper, these will be shown at the conference.** The percentage of the road system in different conditions or risk classes is determined.

Analysis begins with the field data collection, and is about the maximum one person can track and collect (Miller, 1956). About 8-10 miles of road can be surveyed per person-day. Data management adds another 25 percent to total project costs. Surveys and analysis were completed for three watersheds, with additional surveys planned. Application on a random basis is being considered, at least in part, for other forest lands as Oregon's proposed indicators of Sustainable Forest Management. Preliminary analysis for the Wilson River watershed roads indicates open roads are in good condition overall, with surfacing showing the effects of the very wet winter (41 inches of rain at the nearest rain gage during the first month of the survey). Closed roads have higher washout risk, and a greater percentage also blocked by cut and fill slides. An interesting finding is that despite the lack of cross drain culverts on closed roads, hydrologic connectivity is still very low and lower than the connectivity on the open roads. This is probably due to out-sloping, waterbars, and a lot of random drainage. A list of open and closed roads with low attention priority code ratings was developed is being provided to the District road managers.

3. CONCLUSIONS

These performance measures provide reasonably consistent and repeatable information on the environmental risks (or lack thereof) of forest roads in mountainous terrain. They have been used to compare different roads and road systems and develop specific environmental (and maintenance) benchmarks. For example, hydrologic connection of under 20 percent in all ODF watersheds surveyed to date is lower than any reported in the literature. We can show our roads in good conditions, with cross drains are disconnected and not point sources of pollution. One might even argue that we could consider reducing maintenance levels on some of our roads, and except when reopening abandoning roads, reduce the level of repair work. This might allow additional investment in areas where we do not currently have reasonable access, especially in the "Tillamook Burn" where we have many abandoned salvage roads (where despite the extreme fires and salvage, streams have generally high salmon populations, but are lacking in large wood). These results also suggest increased inspection of stream crossings and steep fills is needed for some of the closed roads that have been surveyed.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Effects of Forestry Streamside Management Zones on Water Quality in Virginia*

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Abstract
Forested streamside management zones (SMZs) are widely recommended for the protection of water quality from sedimentation, nutrient inputs and thermal pollution. SMZs are also beneficial for stream channel stabilization and enhancement of in-stream and riparian habitat. Beginning in 2001, sixteen forested watersheds and first order streams/riparian areas were monitored for baseline data prior to treatment installation. Four treatments were installed across four blocks during 2003-2004. Each of sixteen watersheds of approximately 50 acres were clearcut harvested, site prepared with prescribed burning, and planted with loblolly pine (Pinus taeda). Within the watersheds, the streamside management zone treatments were established as 100 feet width with no thinning, 50 feet width with thinning, 50 feet width with no thinning, and a 25 feet "stringer". Each of the four treatments was conducted within one of four blocks (Incomplete Block Design). Currently, we are examining the influence of the SMZ treatments on stream water quality, sediment loading and movement and channel geomorphology in order to identify how much SMZ is needed to protect water quality and how much cost the landowner might incur under differing scenarios. The long term goal is to evaluate trade offs between the water quality benefits of SMZs and costs of SMZ maintenance to landowners. This evaluation process will assist state forestry agencies and landowners in determining how much SMZ and associated costs are necessary to protect water quality during and after forest harvesting operations.

Keywords: streamside management zones, water quality, forestry BMPs.

1. INTRODUCTION

Streamside management zones (SMZs) are widely recommended for the protection of water quality during and after forest harvesting (VDOF 2002, Blinn and Kilgore, 2001). Research has indicated that SMZs can be important for collecting and filtering runoff from harvested sites as well as reducing thermal pollution from direct sunlight (Kochenderfer and Edwards 1990, VDOF 2002). It is also widely accepted that these riparian buffers have significant value as wildlife habitat. Numerous studies have shown the positive impacts of SMZs (Castelle et. al. 1994) but few have investigated the efficacy of various widths and harvest levels.

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 301-305.*

It was hypothesized that different SMZ widths and harvest levels might impact the amount of sediment eroded or deposited near the stream. It was also hypothesized that different SMZ widths and harvest levels might have an impact on stream water quality with respect to nitrogen, phosphorous, dissolved oxygen, temperature and turbidity. Since SMZ maintenance presents a significant cost to landowners (Shaffer et. al. 1998), it is important to determine the comparative benefits of varying SMZ widths and harvest levels. If landowners choose to leave larger SMZ widths with no thinning regime it will likely cost the landowner additional timber revenue and might not guarantee additional water quality benefits.

2. SITE CHARACTERISTICS AND DESIGN

The Piedmont plateau of Virginia is typical of the piedmont in the southeast in general. Elevations range from 200 feet above sea level to the east and 1500 feet above sea level to the west. Local slopes occasionally exceed 30 percent. Extensive agriculture since the 1700s has lead to severe soil erosion and loss of significant site productivity. The watersheds are dominated by old field sites that were abandoned after the civil war and reclaimed by native shortleaf pine (Pinus echinata Mill.) and Virginia pine (Pinus virginiana) as well as a mix of hardwood species such as white oak (Quercus alba), scarlet oak (Quercus coccinea Muenchh.) hickory (Carya spp.), red maple (Acer rubrum), and black gum (Nyssa sylvatica Marsh.). Non-native Loblolly pine (Pinus taeda) plantations were initially planted in the 1970s (Schultz 1997, Gembroys 1974, VanLear et.al. 2004).

This study includes sixteen watersheds in the upper Piedmont Plateau in Buckingham County Virginia. The study is an incomplete block design with four blocks and four treatments. The SMZ treatments are 1) 7.6 meters (25 feet) wide no thin, 2) 15.2 meters (50 feet) wide no thin, 3) 15.2 meters wide thinned, and 4) 30.5 meters (100 feet) wide no thin (table 1). All width designations are per stream side. Pre-harvest data was collected and analyzed in 2002 (Easterbrook 2005). The watersheds were clear-cut in summer and fall 2003. SAS® software (SAS Institute, Cary N.C.) was used to determine significant differences between treatment means by the Tukey-Kramer procedure for all mean comparisons. The incomplete replication is due to technical difficulties on the ground during the harvesting operations.

Table 1. Block and treatment layout showing incomplete replication for the SMZ study.

Tract Name	Block	Treatment
Gunstock 1	1	3 - 15.2 meters wide thinned
Gunstock 2	1	2 - 15.2 meters wide no thin
Gunstock 3	1	4 - 30.5 meters wide no thin
Gunstock 4	1	2 - 15.2 meters wide no thin
Irons 1	2	2 - 15.2 meters wide no thin
Irons 2	2	1 - 7.6 meters wide no thin
Irons 3	2	3 - 15.2 meters wide thinned
Fisher 1	2	4 - 30.5 meters wide no thin
Doe 1	3	4 - 30.5 meters wide no thin
Doe 2	3	1 - 7.6 meters wide no thin
G-U-C	3	3 - 15.2 meters wide thinned
Breezy Bee	3	2 - 15.2 meters wide no thin
Baird-Payne 1	4	1 - 7.6 meters wide no thin
Baird-Payne 2	4	2 - 15.2 meters wide no thin
Miller 1	4	4 - 30.5 meters wide no thin
Miller 2	4	2 - 15.2 meters wide no thin

3. PRELIMINARY WATER QUALITY

It was determined that during the first year after timber harvest there were no significant water quality problems with regard to ammonium, nitrate, dissolved oxygen (DO), or temperature at the α=.10 level (table 2). Other parameters are under investigation (total nitrogen, total dissolved solids, turbidity, and phosphorous) but are not available for analysis at this time. Periodic drought during both the pre and post treatment phase of this study has made it difficult to consistently collect adequate water samples for many of the study streams.

Table 2. Preliminary water quality measurements for the first year after harvest for the SMZ study.

Treatment	NO_3^+ (ppm)	NH_4^+ (ppm)	DO (ppm)	Temp. (C^o)
1 - 7.6 meters wide no thin	0.056 a	0.100 a	10.39 a	15.2 a
2 - 15.2 meters wide no thin	0.043 a	0.097 a	10.85 a	15.2 a
3 - 15.2 meters wide thinned	0.066 a	0.101 a	10.74 a	14.6 a
4 - 30.5 meters wide no thin	0.019 a	0.102 a	10.54 a	14.9 a

The data reveal that there are no significant differences between treatment means at the α=.10 level for all of the water quality indices in table 2. It appears that a SMZ width of 7.6

meters (25 ft) on each side of the stream is adequate to protect water quality with respect to these parameters. It is apparent that thinning timber within a 15.2 meter (50 ft) SMZ does not pose a threat to water quality in these cases. This has important consequences for landowners who want to maximize the timber value removed from their property while protecting water quality in their watercourse.

4. PRELIMINARY COMMERCIAL VALUE

In the Piedmont plateau the commercial value of residual timber across all SMZs was $891.00 per acre. These SMZs are dominated by low value species like red maple, blackgum, and yellow poplar (Easterbrook, 2005). The low overall value of these species made it difficult to thin significant amounts of timber revenue from the SMZs. In most cases loggers would not thin SMZs even when required to do so. Logger reluctance was due to a combination of environmental, production efficiency, and low timber value concerns. The site productivity in these areas tends to be higher than surrounding uplands but lack of active management and desirable shade tolerant species composition makes future revenue from these SMZs marginal also. Shorter rotations of the loblolly pine plantations on the surrounding uplands also make it unlikely that slower growing hardwoods in the SMZs will be available for selection at the next harvest.

These sites demonstrate that there are marginal opportunities for landowners to manage and harvest value from SMZs while adhering to BMPs in the piedmont of Virginia. These riparian zones will likely continue to produce lower value species without active management. Future harvest opportunities will largely be dependent upon the commercial market for hardwood pulpwood and small diameter hardwood logs.

5. CONCLUSION

Sixteen watersheds of approximately 50 acres each were clearcut harvested with conventional rubber tired equipment in the upper Piedmont of Virginia. After one year of soil erosion and water quality study, it is apparent that streamside management zones (SMZs) are important for control of both residual agricultural and harvesting induced erosion in the SMZs. The study also reveals that after one year, harvesting with maintained SMZs had no obvious negative impacts on water quality with regard to nitrate, ammonium, dissolved oxygen or temperature. It is also apparent that in the first year after harvest the minimum SMZ width studied (7.6 meters per stream side) is just as effective at controlling these water quality parameters as wider SMZs of 15.2 meters and 30.5 meters. SMZs of 15.2 meters width per stream side with significant timber thinning were also just as effective as any of the others. This suggests that landowners can leave relatively narrow SMZs (7.6-15.2 meters per side) and thin those SMZs to capture more monetary value from their timber harvest without compromising water quality in the first year. In our 16 watersheds, the reduction of SMZ width from 30.5 meters to 7.6 meters would amount to an approximate average harvestable area increase of two hectares. This would account for an average harvest revenue increase of $6,000-$8,000.

It is important to remember that these study sites will be monitored continuously through 2006. Future efforts will examine additional water quality parameters, erosion sources, and vegetation characteristics.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Impacts on soils from cut-to-length and whole tree harvesting*

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Abstract
A field-based study was conducted to compare the degree and extent of impacts on soils from cut-to-length (CTL) and whole tree (WT) harvesting operations. A CTL harvesting system used less area to transport logs to the landings than did the WT harvesting system (20% vs. 25%). At high moisture level (25 - 30%), both CTL and WT harvestings caused a significant increase of soil resistance to penetration (SRP) and bulk density (BD) in the track compared to undisturbed area ($p<0.05$). Readings of SRP in the track were consistently higher for all soil depths in CTL units than in the WT units while BD changes were greater in the WT units. There was no significant difference in SRP and BD between the undisturbed area and the center of the forwarding trails in the CTL harvest units ($p>0.05$). However, in the WT harvest units SRP and BD readings from the centerline area were significantly higher than those from the undisturbed area ($p<0.05$). Slash covered 69% of the forwarding trail area in the CTL harvesting unit; 37% was in heavy slash while 32% of the trail was covered by light slash. Heavy slash was more effective in reducing soil compaction in the CTL units. Prediction models were developed that can be used to estimate percent increases in SRP and BD over undisturbed areas for both CTL and WT harvesting systems.

Keywords: soil compaction, mechanized harvesting, environmental impacts, soil bulk density, soil resistance to penetration

1. INTRODUCTION

With an increasing demand for the reduction of hazardous fuels and for ecosystem restoration treatments in the Inland Northwest, USA, multiple entries of heavy equipment into forest stands are often required to achieve forest management objectives (Han *et al.* 2006). Managers knowledgeable of different harvesting methods, equipment, and soil conditions want to manage their forests with minimal impact on the productivity of forest soils. Soil compaction occurs as a result of applied loads, vibration, and pressure from equipment that is used during harvesting and site preparation activities (Adams and Froehlich 1984). Soil compaction can be characterized as a breakdown of surface aggregates, which leads to a decrease in macropore space in the soil and a subsequent increase in the volume of soil relative to air space, leading to an increase in bulk density (BD) and soil resistance to penetration (SRP) (Adams and Froehlich 1984). A decrease in soil macroporosity can impede root penetration, water infiltration, and gas

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 307-319.*

exchange (Quesnel and Curran 2000), and these changes can result in a reduction, increase, or no change in tree regeneration and growth.

The degree of soil compaction is related to soil texture (Page-Dumroese et al. 2006), soil moisture, harvesting systems (Adams and Froehlich 1981), slash (Wronski 1980), and the number of machine passes (Soane 1986). Williamson and Neilson (2000) indicated that soils in dry forests or those formed on coarser gravelly parent material resisted compaction more than soils in wet forests or formed from finer-grained materials. Soil moisture at the time of machine traffic has a major influence on the reduction and redistribution of pore space as soils are compacted (Adams and Froehlich 1984). Dry soils are more resistant to changes in pore size distribution and this resistance is reduced as soil moisture increases (McDonald and Seixas 1997). One of the critical factors affecting the degree of soil compaction is the number of machine passes in a ground-based system. Maximum soil compaction normally occurs within the first 10 passes of a harvesting machine (Gent and Ballard 1984) with the greatest impact occurring in the first few passes (Froehlich *et al.* 1980).

In the Inland Northwest, whole tree (WT) and cut-to-length (CTL) harvesting systems are commonly used in mechanized harvesting operations. CTL harvesting is increasingly popular, but about 65% of the harvesting infrastructure continues to be based on WT harvesting systems (Ponsse 2005). Debate over the relative merits of each system has recently been renewed in relation to fuel reduction treatments and small wood harvesting. CTL harvesting has the potential to significantly reduce site related problems such as soil compaction and retention of nutrients on site that can occur with WT harvesting systems. The CTL harvesting process creates a slash mat in front of the machine with tree limbs removed during tree processing at the stump. This slash mat distributes the weight of the harvester or forwarder over a larger area and reduces direct contact between the machine tire and the soil surface. The WT harvesting system drags the entire tree to the landing for processing using a skidder after mechanical felling. The use of WT harvesting systems is popular among fuel reduction proponents because fire hazard is effectively reduced by removing whole trees from high density stands. WT harvesting, however, has high potential for soil compaction and disturbance, because skidder travel tends to sweep duff and litter from trails, exposing bare mineral soil (Hartsough *et al.* 1997).

Our field -based study was performed to broaden existing knowledge on the degree and extent of impacts on soils from CTL and WT harvesting systems on fine-textured soils in northern Idaho. The specific objectives were to 1) quantify the extent of trail area used for primary wood transport, 2) measure the degree of soil compaction before and after harvesting activities, and 3) develop prediction models to estimate the percent increase in soil compaction from baseline data after CTL or WT harvesting.

2. STUDY METHODS

The study site was established on the Potlatch company forest about four miles northwest of Deary in northern Idaho (46º50'27"N, 116º40'42"W). The entire harvesting area was 19.5 ha. Forest cover was predominantly Douglas-fir (*Pseudotsuga menziesii*), grand fir (*Abies grandis*), lodgepole pine (*Pinus contorta*), and western larch (*Larix occidentalis*). The average diameter at breast height (DBH) in the stand was 27 cm and mean tree height was 20 m. The study site was on Helmer (ashy silt loam) and Vassar series (ashy silt loam) soils (Barker 1981). The study site was established in May 2005 and consisted of two units. Each unit was divided into two blocks, creating replicate blocks for the two different harvesting systems (Fig 1). CTL or WT harvesting systems were randomly assigned in each block. Each block was similar in slope, soil, and stand composition.

The harvest prescription for each stand was clearcutting using either CTL or WT harvest systems during May and June 2005. The CTL harvesting system used a harvester and a forwarder. The WT harvesting system used a feller-buncher, a track-based skidder, a processor, and a loader. Harvesting trails were delineated before harvesting to take advantage of topography. Only one or two of the old harvesting trails could be effectively used for this operation; other old trails were not readily useable with the CTL and WT harvest systems.

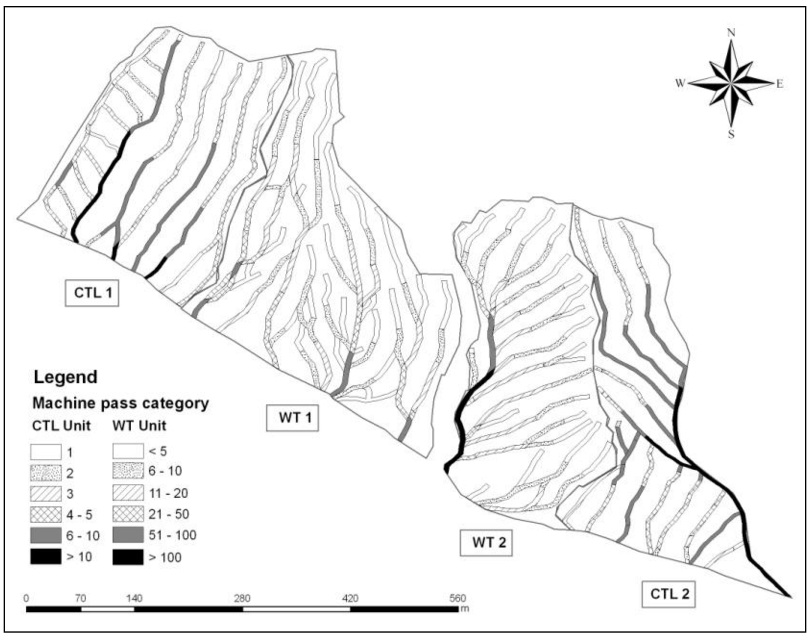


Figure 1. Map of the study site and the trails used by CTL and WT systems

The number of machine passes were mapped over all trails during the harvest operation in each unit. Movements of the harvester and feller-buncher were not included in the number of machine passes since one pass of a tracked machine was not found to significantly impact this soil type (Han *et al.* 2006). A machine pass was defined as one round trip (one round trip = one trip empty + one trip loaded) regardless of whether the forwarder or the skidder was fully or partially loaded with wood. After harvesting, GPS data were collected with a Trimble Geo XT unit at every 15 m along the centerline of the trails to create a trail map. The width of each trail was measured every 50 m to determine the average width of the trail. The GPS and trail width data were used to calculate trail area used for primary wood transport in each harvest unit. A trail map by machine pass category was created using ArcGis 9.1 (ESRI, Inc. 1999; Fig. 1).

SRP was measured using a Rimik CP40 recording cone penetrometer (Agridry, Toowoomba, Australia). To collect SRP data after harvesting, we installed transects across the centerline on all skid-trails at every 30 m. On each transect, we collected SRP at the trail centerline, in both tracks, and in reference sampling points (off-trail area), respectively. Three replicates of SRP were taken at each point.

BD samples were collected along the same transects as SRP, but were located at every 60 m across the centerline. On each transect, BD samples were collected at the centerline, from one of the tracks (left or right), and from the reference area (off-trail area). A core sampler (147 cm^3) was used to collect BD samples at depths of 7.5 cm, 15 cm, and 22.5 cm. Soil cores were placed in plastic bags for transport from the field. In the laboratory, soil samples were weighed, oven-dried at 105 ºC for 24 hrs and reweighed. BD was calculated with the gross soil dry weight and volume of the tube. Soil moisture contents were calculated from each BD sample and additional soil cores were taken before harvest to monitoring soil moisture.

Logging slash was also surveyed along the same transects as the BD samples and SRP data. Slash was classified into three different levels (Bare: no slash, Light: 7.3 kg/m^2, and Heavy: 40.0 kg/m^2). Slash weight was calculated using the downed wood debris survey method outlined by Brown (1974).

Data analysis was preformed using Statistical Analysis System (SAS) (SAS Institute Inc. 2001) and Statistical Package for the Social Sciences (SPSS) (SPSS Inc. 1998). Data were evaluated for normality before running the analyses. The Wilcoxon rank-sum test was used to compare the degree of soil compaction between the two different harvesting systems. The Kruskal-Wallis and multiple comparison tests were performed to test for differences among the three sampling regions (track, center, and reference). These tests were performed separately for each harvesting system (CTL and WT) and at each soil depth (7.5 cm, 15 cm, and 22.5 cm). The effect of slash was tested using a one-way analysis of variance (ANOVA), and regression analysis was used to develop the models that estimate the percent increase of SRP or BD. The significance level was set to 5% ($\alpha = 0.05$).

3. RESULTS AND DISCUSSION

3.1 Soil moisture

Average soil moisture in these study sites was highest in the upper soil layers and decreased with soil depth in all units. Soil moisture was 25 – 30% in the upper 25 cm of soil throughout harvest operations and data collection. There was intermittent light rain for 4 days during the harvesting operation, but it did not cause significant changes in soil moisture at any soil depth ($p<0.05$).

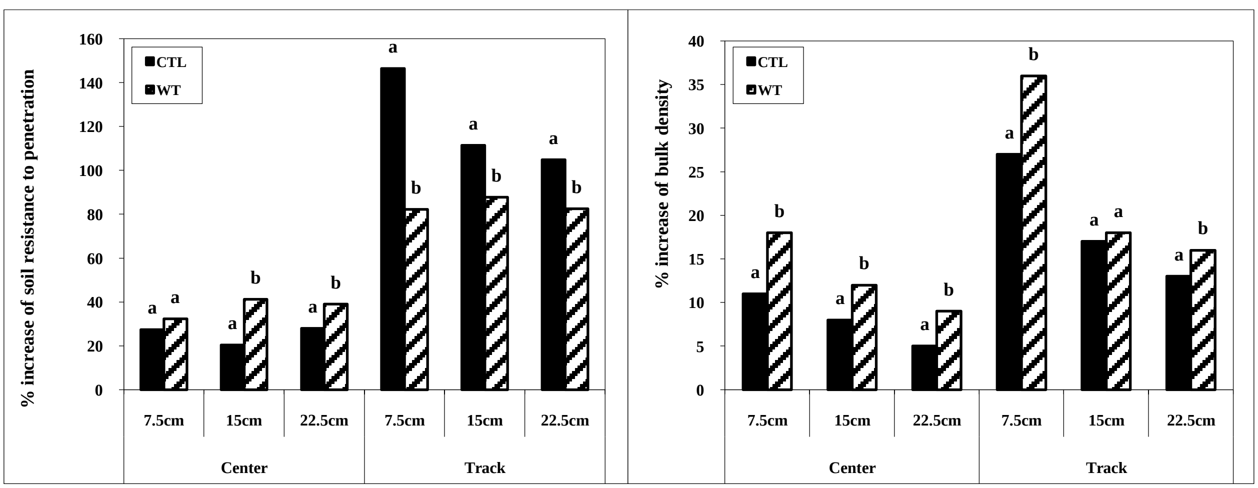
3.2 Soil resistance to penetration (SRP)

After harvesting, a SRP increase was noted in the center and track of the trails in both harvesting units (Fig. 2). For all soil depths, the SRP readings were significantly higher only in the track in the CTL units compared to the reference SRP readings. However, WT harvesting resulted in a significant increase of SRP in both the center and track areas as compared to the reference area ($p<0.05$). In the center of the trail, higher SRP readings were generally found at all soil depths in the WT unit compared to the CTL trail center. Particularly, the percent increase of SRP at 15 and 22.5 cm soil depth was significantly higher in the WT unit than in the CTL unit ($p<0.05$; Fig. 2). The forwarder in the CTL harvesting remained in the wheel tracks created during previous trips and did not drive on the center of the trails. Han *et al.* (2006) found similar results on other fine textured soils in the Inland Northwest, USA, where CTL harvest did not create significant soil compaction in the center of the trail compared to the reference areas.

However, the skidder in WT harvesting systems did not use the same tracks and caused a high degree of soil disturbance within the skid trail. Allbrook (1986) also found that WT harvesting on a sandy loam soil at high soil moisture contents caused a significant increase of SRP in the center of the trails.

In the wheel track, greater percent increases of SRP were found in the CTL than those in the WT unit ($p<0.05$; Fig. 2). The CTL unit had a SRP increase of 105 -147% while it was 82 - 88% in the WT unit. Past studies reported the percent change of SRP from the various soil conditions using CTL and WT harvesting. Han *et al.* (2006) reported in fine-loamy soils that SRP readings increased up to 260% in the track after harvesting using a CTL harvesting system with 21 – 30% soil moisture. Allbrook (1986) found on a sandy loam soil that WT harvesting resulted in 157% increase in the track with soil moisture at 38%. Compared to past studies, this study found a smaller increase of SRP. While this study was performed on a silt loam soil, past studies were mostly conducted on sandy loam soils with soil moisture conditions comparable to this study. Sandy loams, loams, and sandy clay loam soils are more easily compacted than silt loam, silty clay loam, or clay soils in similar soil moisture condition (USDA 1996).

In this study, SRP readings in the track of the trail ranged from 2007 to 2536 kPa in the CTL unit and from 1851 to 2304 kPa in the WT unit. High SRP readings such as those found in our study may be close to the limiting level for root and seedling growth (Greacen and Sands 1980; Sands and Bowen 1978). For example, seedling growth is restricted in 2500 kPa of SRP at dry soil condition (Greacen and Sands 1980). Sands and Bowen (1978) found that a critical soil resistance of 3000 kPa in sandy soils was sufficient to prevent radiata pine root growth. Based on our results, root and seedling growth could be restricted in the wheel tracks of both harvest systems, particularly when the soil is dry.



* Means with the same letter are not significantly different ($p<0.05$)

Figure 2. Percent increase of soil resistance to penetration (SRP) and bulk density (BD) after harvesting

3.3 Soil bulk density (BD)

Pre-harvest BD in the two harvest units was similar ($p>0.05$). BD readings in both the trail center and the wheel track were slightly higher in the WT unit than the CTL unit, but the difference was not significant ($p>0.05$). It was also noted that BD increased with increases in soil depth in both CTL and WT harvesting units.

After harvesting, both the CTL and WT harvest systems caused an increase of BD, but a greater increase in BD was observed in the WT unit in both the center and track of the trail (Fig. 2). In the trail center, while there was no significant difference in BD between the center of the trail and the undisturbed area at any soil depth in the CTL unit, BD in the WT unit was 18% higher in the center of the trail compared to the undisturbed areas (Fig. 2). The percent increase of BD in the WT unit was significantly higher than that in the CTL unit at all soil depths ($p<0.05$).

In the wheel track, both the CTL and the WT systems caused a high percent increase of BD at all soil depths. The largest increase in BD was observed under the track of the trail in each harvesting unit, up to a 36% increase at 7.5 cm of soil depth in the WT unit and a 27% increase at 7.5 cm of soil depth in the CTL unit (Fig. 2). The differences were significant at 7.5 cm and 22.5 cm ($p<0.05$), but not at 15 cm ($p>0.05$). McNeel and Ballard (1992) reported an average BD in the wheel track 20% greater than the measurement from the adjacent control sites in a CTL unit on a sandy loam soil. Allbrook (1986) found that WT harvesting with 38% soil moisture resulted in a 23% increase in soil bulk in the track of trails. Compared to past studies, this study found a smaller increase of BD. These differences may be caused by a combined effect of soil moisture, soil texture, harvesting systems and initial soil properties (i.e. initial BD) (Froese 2004).

Several past studies looked at the relationship between high BD and restricted root penetration and growth. BD that limits roots seems to vary by soil texture, tree species, and experimental conditions (Miller *et al.* 1996). Forristal and Gessel (1955) estimated that 1.25 Mg/m^3 was the upper limit of BD for root growth in sandy loam soils. Heilman (1981) suggested that root-limiting BD was 1.7-1.8 Mg/m^3 in sandy loam to loam-textured soils. Cullen *et al.* (1991) observed no root penetration at BD over 1.9 Mg/m^3. In this study, BD measurements in the wheel track after harvesting in ranged from 1.11 to 1.35 Mg/m^3 in the CTL unit and from 1.19 to 1.37 Mg/m^3 in the WT unit. Compared to past studies, our results indicated that BD on the track of trail in both units would not restrict root penetration and growth.

3.4 The relationship between SRP and BD

For this study, SRP and BD were measured to estimate the degree of soil compaction in each harvesting units. Although both harvesting units had similar soil texture and moisture condition, results from SRP readings in the wheel track were not consistent with those from BD. The different results between the two methods originated from high field variability in the harvesting units as indicated by the large standard deviations. Soil physical properties measured by SRP and BD may vary significantly between two neighboring points in the same area without an apparent cause. Silva *et al.* (1989) suggested that field analyses of soil data are difficult because of its spatial variability and because of the great heterogeneity resulting from several soil formation factors in even homogeneous soils. For example, organic matter content and its distribution in a soil would affect its physical properties including its compactability (Zhang *et al.*1997).

The relationship between SRP and BD has been compared in a few soils. Allbrook (1986) and Clayton (1990) reported that SRP was related positively to BD. They also found that compacted soils showed high increases in SRP, yet only small increases in BD. However, Froese

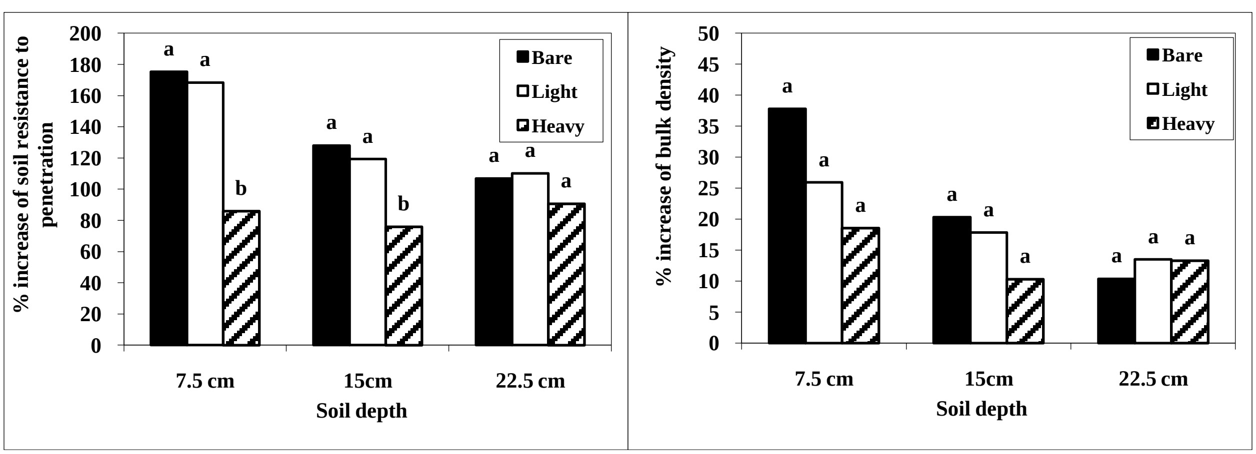
(2004) found that the BD and SRP did not have a strong correlation. In our study, BD was also not strongly correlated with SRP ($r^2 = 0.30$). Soil moisture, soil texture, organic matter content, rock fragments, and field variability are factors often affecting the correlations (Froese 2004). Vasquez *et al.* (1991) also suggested that high correlations between SRP and BD were limited to homogeneous soils under controlled conditions.

3.5 Slash in the CTL harvesting unit

Slash covered 69% of the forwarding trail area in the CTL harvesting unit with 37% of the trail covered by heavy slash and 32% of the trail covered by light slash. In the track of the forwarding trails, heavy slash mitigated the impacts of ground traffic by 89% at 7.5 cm and 53% at 15 cm as compared to SRP readings in bare ground ($p<0.05$; Fig. 4). Several past studies reported that CTL harvesting was a very effective way to minimize soil compaction due to the slash mat created during processing (McDonald and Seixas 1997; Han *et al.* 2006). However, the trail area that is not covered by slash may be severely impacted due to direct contact between the machine track and the soil surface. In this study, while operations on heavy slash (37% of the trail area) showed an increase of up to 86% in SRP and 19% in BD at 7.5 cm soil depth, the 31% of the trail area on bare ground showed a 180% increase in SRP and a 38% increase in BD (Fig. 4).

The buffering effect of slash on soil compaction was found in the heavy slash (40.0 kg/m^2) applied to the track. Light slash (7.3 kg/m^2) seemed to be effective in minimizing soil surface impacts from harvesting activities, but was not sufficient to significantly affect SRP readings ($p>0.05$; Fig. 4). A small amount of slash did not provide enough cushioning in wet soil to absorb the ground pressure and vibration of the harvesting equipment. Light slash tended to be crushed into pieces that could no longer distribute and absorb the impact of the machine. Han *et al.* (2006) reported similar results when a light slash mat (7.5 kg/m^2) was left in a CTL harvesting on wet soil and Jakobsen and Moore (1981) reported that a critical amount of slash required to protect soil is 18 kg/m^2. However, the critical slash amount may change with varying soil textural classes and moisture conditions.

Soil BD was unaffected by slash in the track and center of the forwarding trails at any soil depth ($p>0.05$; Fig. 4). However, there was an indication that both heavy and light slash helped reduce the machine-caused ground pressures at 7.5 cm soil depth in the track of forwarding trails for soil BD.



* Means with the same letter are not significantly different ($p<0.05$)

Figure 4. Percent increase of SRP and BD in the track with different levels of slash in the CTL harvesting unit

3.6 Prediction models to estimate potential soil impacts

For both harvesting systems, prediction models were developed to estimate percent increase of SRP and BD based on the number of machine passes, distance from landing area, initial SRP or BD, and slash amount (Tables 1 and 2). This information is useful when forest managers develop strategies to prevent unacceptable levels of soil damage that may degrade soil productivity. Our prediction equation uses only a few key variables and baseline soil BD or SRP data.

Table 1. Prediction model to estimate percent increase of soil resistance to penetration (Soil moisture content was 25 - 30%)

Harvesting system	Soil depth (cm)	Prediction model	r^2	n
CTL	7.5	% increase = 1819.74 + 32.64ln(M[1]) – 20.23ln(D[1]) – 233.16ln(I[1]) (0.0267)[2] (0.0138) (<0.0001) – 84.62(S1[1]) – 43.35(S2[1]) (0.0003) (0.0269)	0.59	144
	15.0	% increase = 1221.59 + 46.38ln(M) – 16.30ln(D) – 151.04ln(I) – (<0.0001) (0.0014) (<0.0001) 55.03(S1) – 34.56(S2) (<0.0001) (0.0036)	0.65	144
	22.5	% increase = 1260.51 + 50.83ln(M) – 20.96ln(D) – 155.62ln(I) – (<0.0001) (<0.0001) (<0.0001) 25.97(S1) – 17.98(S2) (0.0550) (0.1165)	0.67	144
WT	7.5	% increase = 1156.59 + 13.19ln(M) – 17.69ln(D) – 145.92ln(I) (0.0007) (0.0020) (<0.0001)	0.53	180
	15.0	% increase = 1272.28 + 23.01ln(M) – 16.41ln(D) – 161.66ln(I) (<0.0001) (0.0078) (<0.0001)	0.53	180
	22.5	% increase = 1213.78+ 19.64ln(M) – 20.85ln(D) – 148.86ln(I) (<0.0001) (0.0007) (<0.0001)	0.54	180

[1] M: the number of machine passes, D: the distance (m) from landing area, S1: heavy slash = 1 and others = 0, S2: light slash = 1 and others = 0, and I: initial values for soil resistance to penetration.

[2] Values in ( ) indicate a p-value for testing the significance of each variable that contributes to potential increase of soil resistance to penetration.

Table 2. Prediction model to estimate % increase of soil bulk density (BD) (Soil moisture was 25 - 30%)

Harvesting system	Soil depth (cm)	Prediction model	r^2	n
CTL	7.5	% increase = 68.28 + 0.11ln(M[1]) – 9.35ln(D[1]) – 104.63ln(I[1]) – (0.9832)[2] (0.0034) (<0.0001) 13.63(S1[1]) – 12.62(S2[1]) (0.0593) (0.0501)	0.55	47
	15.0	% increase = 32.67 + 3.63ln(M) – 2.78ln(D) – 51.93ln(I) – (0.3663) (0.2404) (0.0001) 8.49(S1) – 3.02ln(S2) (0.1195) (0.5285)	0.37	47

	22.5	% increase = 51.81 + 2.41ln(M) – 5.20ln(D) – 66.50ln(I) – (0.6011) (0.0642) (<0.0001) 3.64(S1) – 2.66(S2) (0.5573) (0.6309)	0.40	47
WT	7.5	% increase = 16.24 + 5.72ln(M) – 1.14ln(D) – 106.50ln(I) (0.0218) (0.7828) (<0.0001)	0.47	59
	15.0	% increase = 49.35 + 3.57ln(M) – 6.82ln(D) – 47.96ln(I) (0.0109) (0.0043) (<0.0001)	0.49	59
	22.5	% increase = 52.91 +3.73ln(M) – 7.61ln(D) – 41.65ln(I) (0.0251) (0.0081) (0.0008)	0.36	59

[1] M: the number of machine passes, D: the distance (m) from landing area, S1: heavy slash = 1 and others = 0, S2: light slash = 1 and others = 0, and I: initial values for soil bulk density.
[2] Values in ( ) indicate a p-value for testing its significance of each variable that contributes to potential increase of soil bulk density.

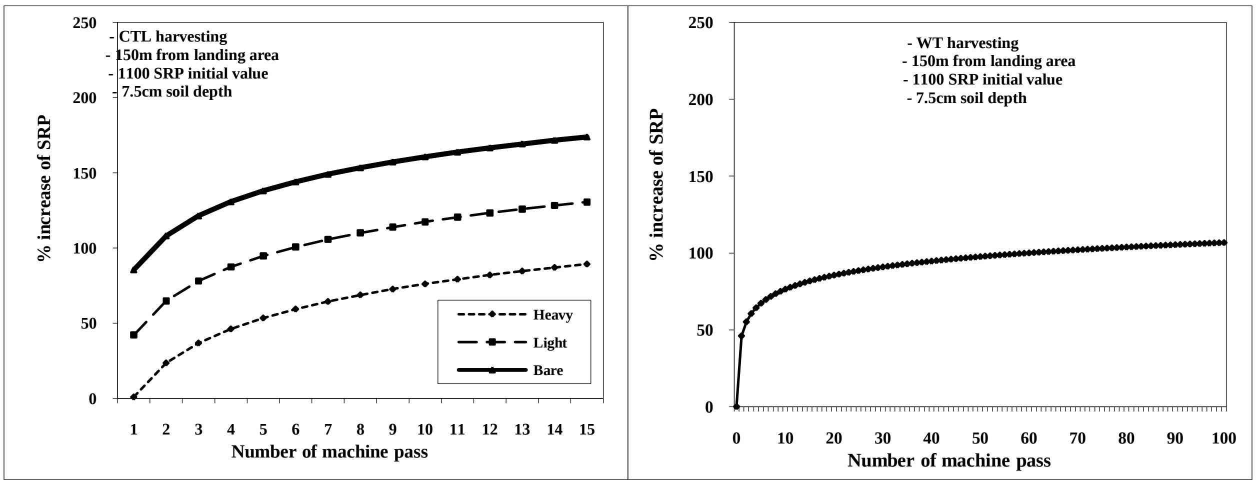


Figure 5. Percent increase in soil resistance to penetration (SRP) as a function of the number of machine passes

Our models indicate that the number of machine passes is highly correlated with increases in SRP in both CTL and WT harvesting systems. However, this was not the case for BD. In the wheel track, most soil compaction occurred after a few passes of a laden logging machine, with 70% of soil compaction in the first 7.5 cm of soil achieved after only 5 machine passes in the CTL unit (Fig. 5). In the WT unit, 80% of soil compaction in the top 7.5 cm of soil occurred after only 10 machine passes (Fig. 5). Soil compaction continued with further passes in both harvesting units, but increase of soil compaction was lower. Similar results have been reported elsewhere. Rollerson (1990) reported that most of soil compaction was achieved after the first 10 to 20 passes in a WT unit. Williamson and Neilsen (2000) found that 62% of final soil compaction occurred after only one pass on skid trails. Han *et al.* (2006) found that there was a rapid increase in SRP up to the second pass of a fully loaded forwarder in a CTL unit.

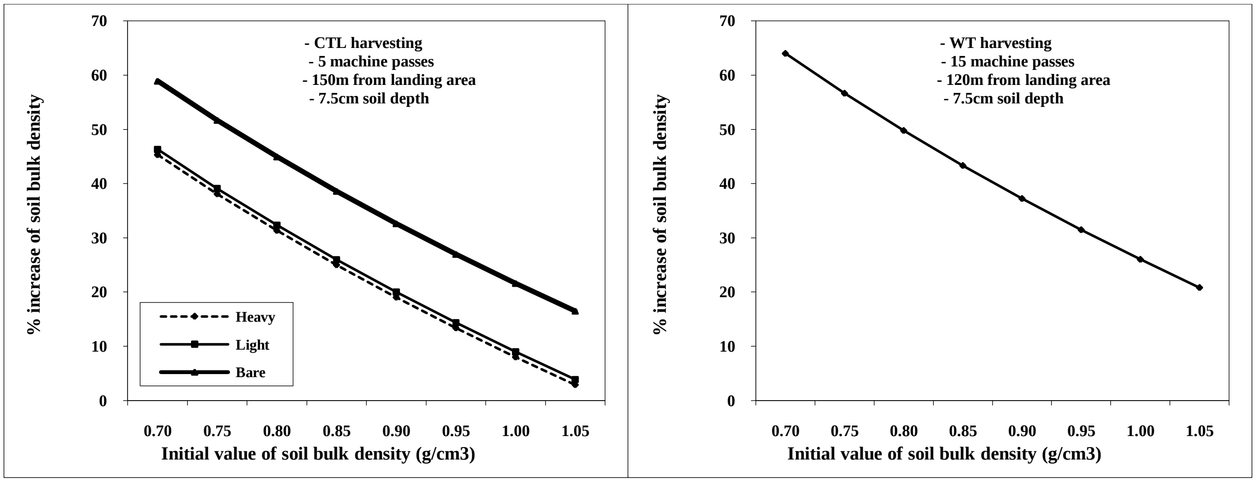


Figure 6. Percent increase in soil bulk density (BD) as a function of initial soil bulk density (BD)

The initial values of SRP and BD had highly negative correlations with their respective percent increases in the prediction models (Fig. 6). The percent increases were greater in soils with lower initial SRP and BD. Page-Dumroese *et al.* (2006) also reported that as initial BD increased, the level of change decreased. These results will be useful in the limitations on harvesting as a function of season. High initial SRP values and BD under dry season conditions may result in less soil compaction after operations (Page-Dumroese *et al.* 2006). Similar results were observed by Williamson and Neilson (2000), and Han *et al.* (2006). They also suggested that scheduling harvest operation for drier conditions could minimize impacts on soils.

The prediction models showed that the percent increases in SRP and BD were negatively correlated with the distance from the landing area. Trails close to the landing area receive a higher density machine traffic results, resulting in greater compaction than areas farther from the landing. Slash in the CTL harvesting unit was effective ($p<0.05$) in predicting percent change of SRP, but it was marginal ($p = 0.0501 – 0.6309$) for BD. The models for SRP ($r^2 = 0.53$ to 0.67) provided better fits to the data than that for BD ($r^2 = 0.36$ to 0.55).

3.7 Extent of soil compaction

Knowledge of the extent of significant damage to the soil is important in assessing effects of harvesting systems (Bettinger *et al.* 1994). The extent of trail area usually varies with terrain, tree size and volume removed, harvesting methods, moisture conditions at harvesting, equipment, and harvesting systems (Miller *et al.* 2004). In this study, The GIS analysis allowed us to determine the percentage of trail area that was trafficked by the skidder in the WT harvest unit and the forwarder in the CTL harvest units (Fig. 1). Although the two different harvesting units had similar terrain, tree density, harvesting method, and moisture conditions at harvesting, CTL harvesting used less area for primary wood transport (20% of total harvest unit) than WT harvesting (25% of total harvest unit). The primary difference in trail area between the two harvesting systems originated from the width of trails. The length of trail was not significantly different between CTL (549 m/ha) and WT (558 m/ha) harvesting, but average trail width in the WT unit (4.55 m) was wider than that in the CTL unit (3.62 m). The forwarder in the CTL harvesting was able to use the same track on subsequent trips, while the skidder in the WT harvesting tended to widen the trail because evidence of the previous track had been erased by the trees being skidded. The average width of the center area between tracks in the forwarding trails was 1.83 m. Similar outcomes were found in past studies (Gingras 1994).

When past studies evaluated compacted area at a CTL harvesting site, they generally included the entire trail, not distinguishing between the center and the track of the trail (Gingras 1994). However, this study found that the center of the trail and undisturbed area were not significantly different in terms of SRP. Therefore, when the compacted area was estimated in this CTL harvesting unit, only the track area of the trail was considered as compacted. The compacted area in the CTL units occupied 10 percent of the harvesting area in this study. Although the center of the track area was not significantly impacted and, therefore, not included in our estimates of track distribution, there still may be impacts on soil productivity as trees growing in the track are likely to intersect the compacted track with more frequency than trees growing in the reference area.

The GIS analysis also allowed us to determine the percentage of trail area by the number of machine pass categories (Fig. 2). The highest percentage of machine passes in the CTL unit fell in the 4 to 5 pass category (32%) while the "less than 5" pass category was highest (34%) in the WT unit. The combined 0 to 20 pass categories accounted for about 85% of the total trail area in the WT unit. In the CTL unit, the combined 3 to 10 pass categories accounted for 75% of the total trail area (Fig. 1). It is difficult to collect this information, but provides a visual representation of heavily trafficked areas and the severity of soil compaction. It also provides a database representing historic use of the site for managers (Bettinger *et al.* 1994). This information may be used to select harvesting systems and trails in future logging operations, and can also assist in establishing plans for tree regeneration in the harvested area.

4. CONCLUSION AND MANAGEMENT IMPLICATIONS

Soil compaction is a common consequence of mechanized forest harvesting operations, especially when soil moisture is high (around 30%). This study was conducted to estimate the degree and extent of soil compaction between CTL and WT harvesting systems in northern Idaho. At high moisture levels, both CTL and WT harvestings caused a high degree of soil compaction in the track of the trails. CTL harvesting left less degree of soil compaction in the trail center and used less area for primary wood transport compared to WT harvesting. Therefore, WT harvesting may require more careful planning and layout than CTL harvesting when forest managers design a harvesting plan using a ground-based harvesting system. Scheduling harvest operations to correspond with dry seasons can effectively minimize soil compaction in both harvesting systems. Slash in the CTL harvesting unit appeared to be effective in minimizing soil compaction, but only about 40% of the CTL forwarding trails was covered by heavy slash (40.0 kg/m^2).

This study also supports the use of designated and old skid trails. High initial BD soils resulted in less change in soil compaction than low initial BD soils. The old skid trails typically have high initial BD. In addition, most soil compaction occurred after a few pass of a laden logging machine in this study. Therefore, traffic restriction to designated skid trails would be an effective strategy to minimize soil compaction on ash-cap soils or fine texture soils that have low initial BD. In this study, we also found that the trails close to the landing area had higher soil densities than trails farther from the landing area. Therefore, when forest managers design harvesting operations, careful attention and additional preparations such as slash treatment could help limit soil compaction impacts on the areas close to log landings.

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Assessing Soil Disturbances Caused by Forest Machinery*

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Abstract
Forest soils are an essential part of the forestry ecosystem; they are anchorage substrate, water and nutrient resource for forest plants and trees as well as habitat of a diverse fauna. However, they are sensitive to any disturbances especially heavy loading. Forest operations commonly use heavy machinery for harvesting and forwarding. Forwarders are among the heaviest equipment used in forestry ranging from 15 to 40 tons loaded and are the ones that require the highest traffic volume to transport wood from felling sites to landings. To quantify the impact of forest machinery on forest soils, soil density and moisture content were recorded before and after forest operations at different research sites as well as after a multi-year period to observe the influence of the freeze-thaw cycle on soil rehabilitation. A nuclear moisture-density gauge was used to determine in situ soil density and moisture content at 5 cm, 10 cm and 20 cm depths of points spaced 50 cm across forwarding trails. This sampling layout ensured capturing the foot prints of the machinery. Soil density and moisture were also monitored after different impact intensities (1, 3, 5, and 10 forwarding cycles). Preliminary results show an increase of soil density in the range of 5 to 20 % after a single cycle. However, no statistical significance was found between the compaction caused after 1 and 3 forwarding cycles for 5, 10 and 20 cm depths.

Keywords: soil compaction; ground disturbances; ground pressure; forest equipment

1. INTRODUCTION

Forest soils are an essential part of the forestry ecosystem; they are anchorage substrate, water and nutrient resource for woody plants as well as habitat of a diverse fauna. The stability and productivity of forest stands are mainly related to the quality and integrity of forest soils. In order to maintain both stability and productivity of forest stands, negative impacts on soils by forest operations have to be minimized. Although comprehensive research focuses on increasing stand productivity, wood quality and efficiency in forest operations additional emphasis is required to assure forest soils are properly protected. Therefore, sustainable management practices should involve the control and prevention of unacceptable rates of erosion, nutrient loss, landslides, excessive compaction, puddling and mixing of topsoils and subsoils, during and after forest operations (Forest Practices Board 2000). One of the most damaging effects caused by forest machinery is soil compaction which is defined as an increase in bulk density (increased mass per unit of volume) (Dickerson 1976, Froehlich 1979, Steinbrenner and Gessel 1955). Surface pressure pushes the particles of soil closer together thus reducing the volume of air filled

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 321-332.*

voids (Craig 1997). Consequently, the particles are reoriented into a configuration that has a higher bulk density (Cassel 1983). Soil densification has a direct impact on plant and tree growth since it reduces the water infiltration rate and slows down gas and nutrient exchange by decreasing the amount of pore space, especially macropores (Forristall and Gessel 1955). The highest degree of compaction typically occurs in the top 30 cm of a soil profile, which normally contains most of the root mass (Wingate-Hill and Jakobson 1982). As the penetration resistance generally intensifies with an increase in density, a greater mechanical resistance of the soil to growing roots was observed (Russel 1977, Vepraskas 1988). Furthermore, roots can be injured directly by the action of the wheels of the equipment going over the forest floor (Olson 1952, Wronski 1984). All these modifications of the soil structure may considerably reduce vegetation growth. After subsoil compaction, Murphy et al. (2004) reported that reduced growth resulted in a 42 % decrease of stand volume which translates to a 60 % decline in value.

Nowadays, most forest operations require the use of heavy machinery in order to be competitive. The Canadian forest industry performs two main felling and extraction methods, the cut-to-length (CTL) and tree length methods. CTL logging is a system for mechanized forestry harvesting where trees are delimbed and cut-to-length directly at the stump area. CTL is typically a two man, two machine operation with a harvester felling, delimbing and bucking trees and a forwarder for timber transport. This system has been utilized in Canada since the 1970's but has gained much popularity especially in the Atlantic provinces over the past decade where more than 75 % of the wood is currently harvested with the CTL method.

Forwarders as part of the CTL harvesting system are among the heaviest equipment used in forestry ranging from 15 to 40 tons loaded and are the ones that require the highest traffic volume in order to transport wood from the felling site to the landing areas close to a road accessible by trucks. Besides the travel speed, the payload of the forwarder determines its productivity. Increasing any of these two parameters can expand the environmental risk caused by the machine (Nugent et al. 2003). Wheeled or tracked vehicles cause compaction on soils by 1. the normal vertical force due to the static and dynamic load of the wheels (axle loads), 2. shear stress caused by slippage of wheels or tracks, and 3. vibration of engines that are carried through tires or tracks (Kozlowski 1999). The normal force exerted by a machine is the basic cause of subsoil compaction (Taylor and Gill 1984, Håkansson et al. 1987).

Soil susceptibility to compaction is dependent on many intrinsic properties such as soil texture (Bodman and Constantin 1965), parent material (Wasterlund 1985) and moisture retention properties (Williams and Shaykewich 1970, Vepraskas 1984). Directly related to this susceptibility is the rehabilitation capabilities of a soil after disturbance which are dependent on soil structure, texture, moisture content as well as severity and depth of compacted area (Brais 2001). Forest soils are not only sensitive to disturbances but may also require a long time to rehabilitate. Residual forest soil compaction has been reported for periods ranging from 15 (Froehlich et al. 1986) to 55 years (Power 1974). Due to the limited reversibility of subsoil compaction, stresses exceeding the soil's range of elastic behavior which results in plastic deformation have to be avoided (Berli et al. 2004).

Research is therefore required to evaluate the degree of compaction caused by CTL forest machinery on forwarding trails over a multi-year period with respect to different equipment configurations, transport cycles and site conditions.

1.1 Research objectives

The research project described in this article aims at determining the impact of forest machinery on soils by measuring soil density and moisture content before and after harvesting and forwarding. In addition, it analyses the degree of soil recovery with regards to soil density from disturbance of forest machinery after a multi year period compared to the properties measured before and after the disturbance.

2. MATERIALS AND METHODS

The field work for this project commenced in July 2004 and will continue for several years. The disturbances caused by CTL forest operations will be analyzed on different forwarding trails by measuring soil density and moisture before and after forest operations. The experimental layout is very similar for each research site since the main objective is to measure soil density and moisture. Different forwarding trail traffic intensities are studied for both research sites in CFB Gagetown while the mitigating effect of slash is the main focus in Blackbrook.

2.1 Location and description of research sites

Due to the high variability of forest stands, soil texture and moisture content conditions, several sites have to be studied. The selection criteria for these forest stands are harvesting and extraction method, season of operation, site accessibility as well as site conditions. This research project focuses on the four research sites that are currently being studied in New Brunswick (Figure 1). The terrain elevations for these sites vary from 60 to 250 m above sea level (a.s.l) with slope gradients ranging from 2 to 12 % (Table 1).

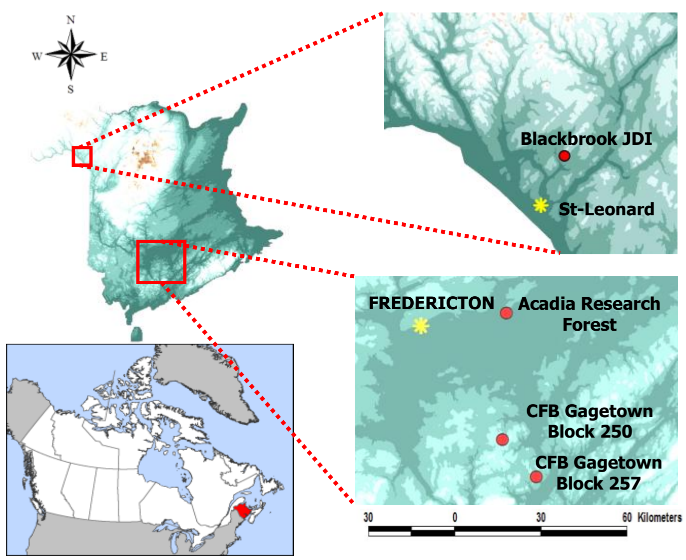

Fig. 1. Location of research sites

A pure white spruce plantation is the forest cover type for the site in northwestern New Brunswick (Blackbrook) while the sites in central New Brunswick (Acadia and CFB Gagetown) are respectively balsam fir and mixed softwood stands.

Table 1. Physical description of research sites

Research sites	**Coordinates**	**Elevations a.s.l (m)**	**M.A.R (mm)**	**Soil texture**	**Forest cover**	**Merch. V. (m^3/ha)**	**Type of harvest**
Gagetown **Block 250**	45°46′15″ N 66°26′53″ W	64 – 72	900	Silt loam / loam	Mixed softwood	105	C.C
Gagetown **Block 257**	45°31′33″ N 66°18′07″ W	122 - 136	914	Silt loam / loam	Mixed softwood	112	C.C
Acadia Research Forest	49°59′24″ N 66°18′36″ W	60 - 70	939	Compact Clay loam	Balsam fir	N/A	C.T
Blackbrook J.D. Irving	47°26′26″ N 67°50′60″ W	250	769	Silt loam / loam	White spruce	N/A	C.T

M.A.R. = Mean annual rainfall C.C = Clear cut N/A = Not available Merch.
V. = Merchantable volume C.T. = Commercial thinning

2.2 Forest machinery

When considering operational variables, forwarders vary in tare-weight from 7 to 20 tons. Since the tare-weight of the machinery is stable and can not be modified without structural changes, this study focuses on the area of contact between the machinery and the soil which translates to ground pressure as well as the load capacity of the log bunk (Table 2).

Table 2. Machinery specifications for each research site

Research sites	**Make and Model**	**Traction type**		**Empty mass (kg)**	**Load capacity (kg)**	**Loaded mass (kg)**	**Ground pressure (EMPTY)**		**Ground pressure (LOADED)**	
		Rear axle	**Front axle**				**Front (kPa)**	**Rear (kPa)**	**Front (kPa)**	**Rear (kPa)**
Gagetown **Block 250**	Tigercat H822 [1]	R.S.T		26, 490	**N/A**	**N/A**	60.4		**N/A**	
	Rottne Rapid SMV [2]	S.F.T	Chains	14, 200	16, 000	30, 200	61	30	78	92
Gagetown **Block 257**	John Deere 120 [1]	R.S.T		18, 379	**N/A**	**N/A**	40.5		**N/A**	
	Timberjack 610 [2]	F.T	F.T	12, 800	8, 000	21, 800	43.4	34.5	49.6	88.3
Acadia Research Forest	Ponsee Beaver [1]	S.T	S.T	13, 900	**N/A**	**N/A**	59	29	**N/A**	
	Timberjack 1010D [2]	S.F.T.	S.T	12, 500	10, 000	22, 500	54	29	54	79
Blackbrook J.D. Irving	Enviro [1]	S.T.	S.T.	10, 000	**N/A**	**N/A**	45 - 55*	25 - 30*	**N/A**	
	Rottne Solid F9 [2]	S.F.T.	Chains	11, 500	9, 000	20, 500	50	30	61	82

[1] = Harvester **S.F.T** = Steel flexible tracks
N/A = Not applicable [2] = Forwarder
F.T = Flotation tires (109 cm wide) * = Approximate
R.S.T = Rigid steel tracks **S.T** = Stock tires

2.3 Field sampling and measurement

2.3.1 CFB Gagetown

In each cut-block (250 and 257), a forwarding trail of ± 190 m in length and 5 m wide was designed prior to forest operations (Figure 1). Their location was based on accessibility (proximity to main landing), avoidance of terrain obstacles (large boulders and high rock content) as well as topography (avoiding steep slopes). Along the forwarding trail, four compartments were established to analyze the impact of traffic intensity on soil compaction. This was done by varying the number of forwarding cycles i.e. one cycle is one pass-over without a load and one pass-over with the log bunk filled with wood. Each of these compartments was 5 m wide and 20 m in length. Soil density and moisture was measured in each compartment perpendicular to the axis of the forwarding trail at locations systematically spaced 50 cm apart along the full width of the trail in order to capture the foot prints of the machinery that was going to be driven over the area. In total, nine measurements (which constitute a line) were recorded across the forwarding trail and a total of four lines were studied per compartment. These lines were grouped in pairs spaced by one meter and 15 m between each pair. Adjacent to each pair of lines were control zones consisting of two lines of four measurement points per line that remained undisturbed throughout the study. In total, 208 measurement points per block were studied along the forwarding trails while 64 of these were located in the control zones. At each measurement point, *in situ* soil density and moisture content was determined by a nuclear moisture-density gauge at 5 cm, 10 cm and 20 cm depths, all measured at the same location. After the initial pre-harvest readings were completed, the block was harvested with the equipment described in (Table 2) and special care was given to keep the trail free of any slash (i.e. small tree branches and non-merchantable logs) in order to determine the maximum impact of the equipment. A single pass over with the harvester was allowed inside each forwarding trail. Once the wood was harvested, different traffic intensities (forwarding cycles) were simulated by driving the forwarder a certain number of times over the compartments (1, 3, 5, and 10 times) without a load and with a full consistent load. A set of measurements was recorded in each block before and after forwarding and forwarding. Additional readings will be recorded in the same locations in summer and fall 2006.

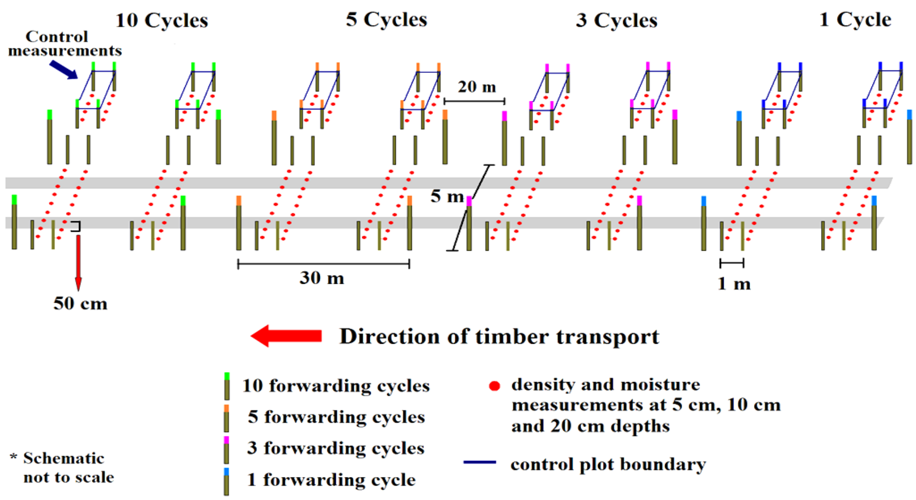

Fig. 1. Forwarding trail and sampling layout of block 250 located in CFB Gagetown

2.3.2 Acadia Research Forest

Prior to the commercial thinning operation, a design of 32 forwarding trails was carried-out with an outside trail spacing of 15 m, four of them were chosen to be monitored over a multi-year period. The selection of trails to be monitored was based on two variables. The trails had to be spatially distributed over the entire area in order to capture the variety of terrain topography and soil properties. The average length of the forwarding trails was 77 m and 4 m in width. Study plots were established within the respective forwarding trails, either at 30 and / or 60 m from the main road. Soil sampling was done along each cross section of forwarding trails at the different measurement plots. Each measurement point was exactly 50 cm apart except for the middle of the cross section (trail centerline), where a 75 cm space was left between each adjacent point. All controls established in this experiment consisted of three cross sectional lines spaced one meter apart which were located in the same orientation as the main plots and had a total of nine measurement points. *In situ* soil density and moisture contents were determined with a Campbell MC-1 nuclear-density gauge at 5, 10 and 20 cm depths. The dates readings were taken can be seen in (Table 3). A set of measurements will also be recorded in summer and fall of 2006.

2.3.3 Black Brook

The general setup of this experiment is similar to the one found in CFB Gagetown but focuses on the mitigating effect of slash on the forwarding trails. However, forwarding trails had an average length of 90 m and a width of 3.3 m. Once again, *in situ* soil moisture and density was recorded with the nuclear gauge at three different depths (5, 10 and 30 cm) in the same location. In total, six plots were designed for each of which two lines of seven cross-sectional readings were recorded before and after harvesting and forwarding operations. Control zones were established before operations where two lines (spaced by one meter) of three readings were measured 1 m apart. While harvesting and forwarding took place, two of the six study plots were covered with slash and the remaining four plots had no slash on the forwarding trail to quantify the full impact of the machinery. Because of the limited length of the forwarding trails, only 1 or 2 forwarding cycles were completed in each plot. Following the forwarding, slash samples covering an area of 1 m^2 were transported back to the lab to determine their moisture content and mass (kg/m^2).

Table 3. Dates and number of soil density and moisture content readings recorded at different locations

Research sites	**Dates of readings**						**Location**	**N / depth (cm)**			
	Pre Harv.	**Harv.**	**Post Harv.**	**1st Spring**	**1st Fall**	**2nd Spring**		**5**	**10**	**20**	**30**
Gagetown **Block 250**	Aug. 15th/05	Jan. 6th/06	May 5th/06	-	-	-	Under tires	66	66	66	-
							Outside of tires	60	60	60	-
							Control	56	56	56	-
Gagetown **Block 257**	Aug 20th/05	Oct. 3rd/05	Oct. 4th/05	May 4th/06	-	-	Under tires	36	36	36	-
							Outside of tires	36	36	36	-
							Control	32	32	32	-
Acadia Research Forest	Aug. 4th/04	Aug. 15th/04	Oct. 15th/04	May 18th/05	Sept. 9th/05	May 1st/06	Under tires	56	56	56	-
							Outside of tires	112	112	112	-
							Control	72	72	72	-
Blackbrook J.D. Irving	Nov. 11th/05	Nov. 12th/05	Nov. 13th/05	May 12th/06	-	-	Under tires	50	50	-	50
							Outside of tires	34	34	-	34

Control	24	24	-	24

Harv. = Harvest

2.4 Materials

2.4.1 Nuclear moisture-density gauge

Determining soil moisture and density usually requires the disturbance of the study area in order to insert a cylinder of known volume into the soil and to extract the sample. Raper and Ebrach said that "*…it is disturbing that a method with this many inherent errors is referred to as a standard*". This research focuses on a non intrusive method of determining soil moisture and density by using a nuclear density gauge.

With the exception of Acadia Research Forest site, *in situ* moisture and density measurements were recorded with the Humboldt 5001 EZ nuclear moisture-density gauge. This equipment automatically computes a variety of parameters, including direct readouts of wet density, dry density, moisture content, percent of moisture, percent of compaction (Proctor or Marshall), void ratio as well as air voids. For this research focus is given to wet and dry density as well as moisture content of the soil. The density measurement is based on the attenuation of gamma radiation due to Compton scattering and photoelectric absorption directly related to the electron density of materials. This indicates the mass density of materials with a chemical composition similar to the crust of the earth (Humboldt Scientific 2000). The gamma source is located at the end of the source rod, which can be lowered to desired depth at 5 cm increments, up to 30 cm. The sensor that collects the backscattering of gamma radiation is located at the bottom of the nuclear moisture-density gauge itself which is placed on the ground. As for the moisture content, its measurements are based on the thermalization (or slowing down) of fast neutron radiation, which is a function of the hydrogen content in the materials. Both source and sensor for neutrons are located at the bottom of the nuclear gauge (Humboldt Scientific 2000). A Campbell MC-1 nuclear moisture-density gauge was used in Acadia. The same theory applies although the Campbell requires additional transformation of the density and moisture count read-outs.

3. RESULTS AND DISCUSSION

Since this is an on-going research project and some of the data was recently collected, what follows are preliminary results originating mostly from block 257 (CFB Gagetown).

3.1 Soil density

The difference between pre and post harvest lines perpendicular to the forwarding trail show an increase in dry density where the machinery made contact with the soil both at the 5 and 20 cm depths (Figure 2). There is no statistical difference (P = 0.141, N = 10) between pre and post harvest dry density readings at the 5cm depth. However, there is a statistical difference (P = 0.010, N = 10) between pre and post harvest dry density readings located underneath the wheels at a 20 cm depth. There is no statistical difference between the compaction caused by the machinery at the 5 cm and 20 cm depths (P = 0.919, N = 10). The root and stump network found in forest soils can act as a complex pivotal system that can attenuate pressure on one side and provide additional down force on the opposing end. Consequently, the pressure applied by a forwarder's tire could possibly be displaced vertically thus increasing the disturbed area. This root mattress could be a possible explanation towards the dry density variation between pre and post harvest readings located outside the tire tracks of the equipment.

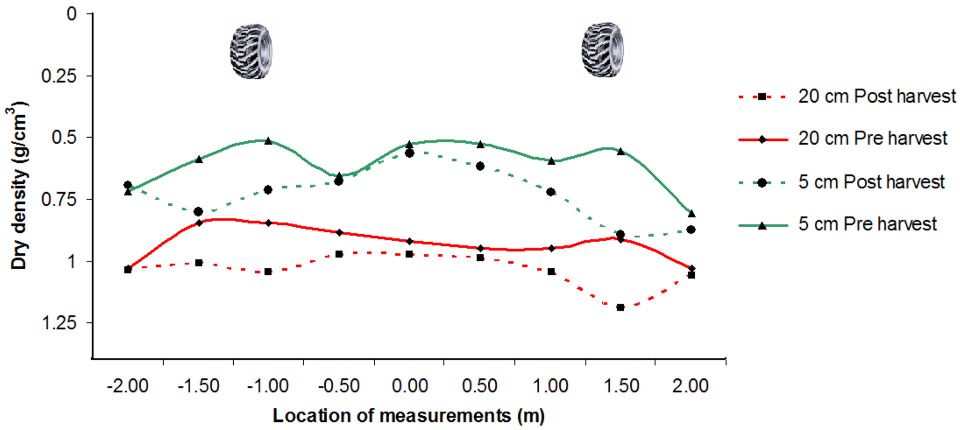

Fig. 2. Pre and post harvest soil dry density (g/cm^3) in relation with the location of measurements on the forwarding trail for cycle 3 (line 1 and 2) of block 257

In the majority of the cases, compaction occurred at all three depths of measurements with the exception of cycle 10 (Table 4). The soil in cycle 10 (block 250) had very high water content (59 % at 20 cm to 110 % at 5 cm depth) when post harvest readings were recorded. Furthermore, even though block 250 was a winter harvest (January 2006), severe ruts (35 to 50 cm in depth) were created in the compartment where 10 forwarding cycles were studied. In this compartment, plastic deformation of the soil was the main effect of the pressure applied by the equipment and not compaction itself. Concerning block 257, (CFB Gagetown) a statistical difference was found at the 20 cm depth between pre and post harvest readings after a single cycle. In the same block, a statistical difference was found at the 10 and 20 cm depth following 3 forwarding cycles. The average compaction, all depths combined was 12.2 % and 15.6 % respectively after 1 and 3 cycles. With regards to block 250, very little compaction (3.9 %) was caused after the first forwarding cycle while close to 18 % was measured after 5 cycles at the 20 cm depth.

3.2 Soil moisture

Soil water content tends to decrease with depth (Figure 3). Furthermore, the water content range for each depth seems to narrow as depth increases from 5 to 20 cm. This can partly be explained by the higher organic matter content at shallow depths which can have significantly high moisture contents. The compaction at different depths tends to decrease as water content increases (Figure 4). At high water contents, plastic deformation can occur due to the replacement of air filled voids by water which can cause severe rutting since water can not compress and is therefore supporting part of the load. Half of the entire compaction that was caused can be explained by 30 % of the points located in the water content range of 25 to 35 % (moist soil). The majority of this compaction occurs at the 10 to 20 cm depths which contains a great part of the root mass.

Table 4. Effects of forwarding cycles on soil dry density recorded at different depths between pre and post harvest readings

		Pre vs. Post				Pre harvest		Post-harvest			
Block	**Cycle**	**Depth (cm)**	**N**	**F**	**P α=0.05**	**ρ_{dry} (g/cm^3)**	**ω (%)**	**ρ_{dry} (g/cm^3)**	**ω (%)**	**% incr.[1]**	**Com.[2] (g/cm^3)**
257	**1**	5	17	1.51	0.228	0.726	32.6	0.830	59.4	12.5	0.104
		10	17	2.85	0.101	0.854	26.8	0.973	45.5	13.1	0.128
		20	17	5.00	0.032*	1.006	21.6	1.132	35.8	11.1	0.126
	3	5	19	3.25	0.080	0.629	40.2	0.749	61.2	16.1	0.120
		10	19	6.66	0.014*	0.762	32.7	0.905	46.9	15.8	0.143
		20	19	12.19	0.001*	0.886	25.6	1.042	39.8	14.8	0.154
250	**1**	5	21	0.51	0.479	0.758	24.7	0.791	47.6	4.1	0.033
		10	21	0.64	0.429	0.939	19.5	0.976	38.5	3.8	0.037
		20	21	1.24	0.272	1.156	15.7	1.213	29.8	3.9	0.047
	3	5	20	2.01	0.164	0.771	28.7	0.845	38.8	8.8	0.074
		10	20	6.29	0.017*	0.936	23.2	1.052	30.3	11.0	0.116
		20	20	19.49	0.000*	1.061	20.1	1.294	26.2	17.8	0.233
	5	5	18	0.36	0.553	0.699	32.1	0.729	62.0	4.1	0.030
		10	18	3.04	0.090	0.850	25.9	0.923	48.4	8.10	0.075
		20	18	8.77	0.006*	1.004	21.7	1.188	39.2	15.5	0.184
	10	5	7	0.10	0.760	0.636	31.7	0.601	109.7	-5.9	-0.035
		10	7	0.35	0.564	0.841	23.7	0.778	81.5	-8.1	-0.063
		20	7	0.01	0.905	1.005	19.7	0.997	58.6	-0.9	-0.009

***** = Significant at the 0.05 probability level
ω = Water content
[1] = Dry density percent increase between pre and post harvest readings
[2] = Compaction

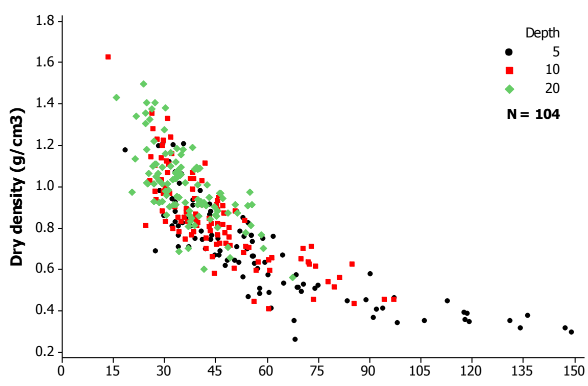

Fig. 3. Post harvest dry densities (g/cm^3) in relation with water content (%) at different depths

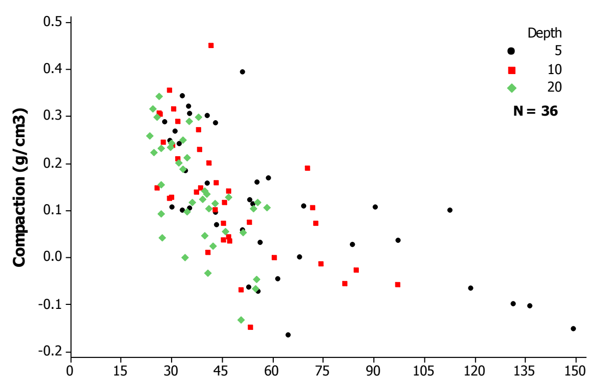

Fig. 4. Compaction (g/cm^3) in relation with water content (%) at different depths

3.3 Soil rehabilitation

Soil density tends to increase linearly as depth increases (Figure 5). This is true for up to 20 cm depth in this study. The degree of compaction (post harvest – pre harvest) seems to be similar between 1 and 3 cycles although initial dry density was lower in cycle 3. Soil rehabilitation is more apparent in the cycle 3 than cycle 1. In order to understand why this trend is occurring, moisture content and organic matter content were added to the graph. Moisture contents of spring readings are higher in cycle 3 than cycle 1, 55 % to 34 % respectively which reduces soil dry density. Furthermore, the 5 cm layer in cycle 3 has a high organic matter content (57 %) compared to cycle 1 at 15 %. Organic matter has a high water retention capability and a low specific gravity (± 0.80) which can influence the moisture content readings of the nuclear gauge which then impacts the dry density.

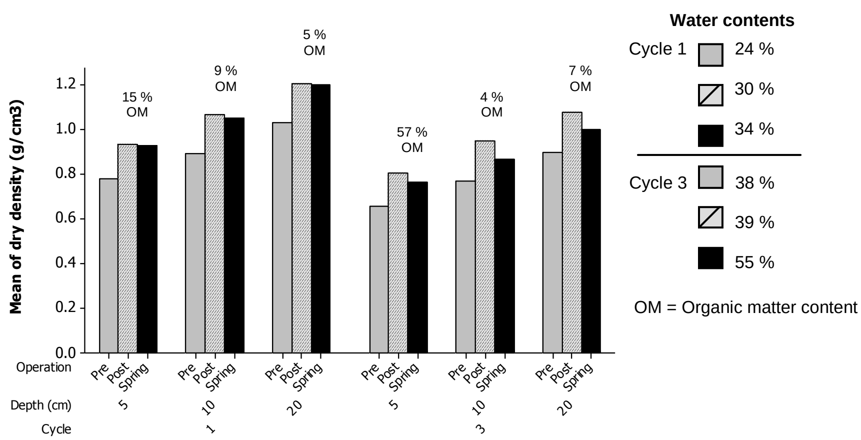

Fig. 5. Temporal variation of soil dry density (g/cm^3) located under tires in relation with different depths and forwarding cycles for block 257, line 1

4. CONCLUSIONS

Economically feasible operations rely on the use of heavy equipment to harvest and transport wood from the felling site to the landings. Forwarders used in the CTL method are the heaviest equipment used in forestry and have the highest traffic volume making them a high risk to cause soil disturbances. This study showed a single cycle (one pass-over empty and one pass-over with the log bunk full) created a 12.2 % increase in soil dry density within the first 20 cm of soil. However, there was no statistical difference between cycle 1 and cycle 3 with regards to soil compaction. The best method to minimize ground disturbances is to conduct forest operations when the soil water content is low in order to keep compaction and plastic deformation at a minimum.

5. ACKNOWLDEGEMENTS

This research was funded by the Canadian Foundation for Innovation (CFI), the New Brunswick Innovation Foundation (NBIF) as well as the University of New Brunswick. The authors would like to extend special thanks to the following contributors; Edwin Swift from the Canadian Forest Service, Patrick Jones and Kevin Smith from the Canadian Forces Base Gagetown and Gaetan Pelletier from J.D. Irving for their collaboration.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Effects of Soil Compaction on Residual Stand Growth in Central Appalachian Hardwood Forest: A Preliminary Case Study*

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Abstract
A preliminary study that quantified the impacts of soil compaction on residual tree growth associated with ground-based skidding traffic intensity and turn payload size was investigated in the central Appalachian hardwood forest. The field study was carried out on a 20-acre tract of the West Virginia University Research Forest. Skid trails were laid out in 170' – 200' sections, which allowed for one 50'treatment and two 50' replications of each treatment over the total skid trail. Treatments were arranged in a 3x3 factorial with three payload sizes of unloaded, half capacity, and full capacity and the number of loaded machine passes set at 1, 3, and 5. Three skid trails underwent no skidding activity in order to serve as control treatments. A John Deere 640G III cable skidder was employed to simulate the extraction operations. Measurements included soil type, pre-treatment and post-treatment soil bulk density and soil moisture, understory vegetation, and site slope and aspect. Merchantable hardwood trees within a 30-foot range of the centerline were randomly selected and measured for DBH, total height, merchantable height, grade, crown size, and growth rate. Each individual tree's geographic location was determined by GPS. Preliminary results suggest the interrelationship among traffic intensity, payload, and soil compaction. The comparison of initial and subsequent tree and soil measurements can be used to examine residual tree growth and soil compaction recovery in a further study.

1. INTRODUCTION

All harvesting operations cause some compaction, but the degree of compaction varies with harvesting equipment, techniques, intensity, and soil properties, especially moisture content and texture (Reisinger et al. 1988, Reisinger and Aust 1990, Aust 1994). Many studies have been conducted on the effects of timber harvesting as a silvilcultural activity on erosion and sedimentation and best management practices (BMPs) compliance and effectiveness (Kochenderfer et al. 1997, Briggs et al. 1998, Egan et al. 1998). Many studies compared the area disturbed by conventional logging with a tractor or skidder to a skyline system. Steinbrenner and Gessel (1955) studied tractor harvested areas in western Washington and found 26 percent of the total area to be occupied by tractor skid roads. Wooldridge (1960) compared soil disturbances by skyline-crane harvesting with those by conventional tractor skidding. In the tractor-harvested area, 29.4 percent of the ground surface was disturbed, while only 11.1 percent was disturbed in

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 333-341.*

the skyline area. Dyrness (1965) stated the tractor-harvested unit had approximately three times more area in the compacted disturbance class than did the high lead unit. Dickerson (1976) reported that 21% of the soil on a clearcut stand was disturbed compared to 14% for an area with a selective cut. Dickerson also found twice as much severely disturbed soil (barred, rutted, and compacted) on the clearcut operation. Soil disturbance averaged 17% in selection cuts and 28% in strip and patch clearcuts of northern hardwoods (Nyland et al. 1977).

The forest floor has been found to be very susceptible to disturbance by harvesting operations (Turcotte et al. 1991). Soil compaction and loss of organic matter from the forest floor had a direct influence on the weathering rates of minerals, nutrient mineralization and consequently plant growth. Mechanical disruption of the forest floor might have an adverse impact on site productivity because the forest floor was a major source of nutrients for shallow rooted spruce and fir seedlings (Hoyle 1965, Shaw et al. 1987).

During the past decade, timber harvesting methods in central Appalachia have evolved to some extent. However, chainsaw felling and rubber-tired cable skidding is still the dominant system in the region due to terrain limitations and constraints surrounding the hardwood species. The soil bulk density changes associated with conventional manual and mechanized harvesting systems have been studied (Wang et al. 2005). In this study, we wanted to quantify and document how traffic intensity and payload of a typical rubber-tired cable skidder affected soil compaction and the residual stand growth in the region.

2. MATERIAL AND METHODS

2.1 Site and Skid Trails

The field data collection was carried out on a section of the West Virginia University Research Forest from May to July in 2005 and the site was selected as a representative sample of the central Appalachian hardwood region in respect to tree age and species composition. The study area was 20 acres in size, relatively flat, and of the same general southwestern aspect with the elevation of approximately 2000 feet (610 m) (Figure 1). The soils of the area are comprised of three associations. The Dekalb-Buchanan-Lily and Hazelton-Dekalb-Buchanan associations make up the majority of Research Forest, and are generally gently sloping to very steep, well drained and moderately well drained, acid soils; found on uplands and foot slopes. A smaller area of the Gilpin-Wharton-Ernest association is found in the northwestern portion of the Forest, and this association is more alkaline than the other two soils. The major species composing the WVU Research Forest are red oak *(Quercus rubra)*, yellow-polar *(Liriodendron tulipifera)*, red maple *(Acer rubrum)*, chestnut oak *(Quercus prinus)*, and black cherry *(Prunus serotina)*. Other species found within the forest are cucumber tree *(Magnolia acuminata)*, scarlet oak *(Quercus coccinea)*, black gum *(Nyssa sylvatica)*, sassafras *(Sassafras albidum)*, and American beech *(Fagus grandifolia)*.

Skid trails were laid out in 170 to 200 feet sections, which allowed for one 50-foot treatment and two 50-foot replications of each treatment over the total skid trail (Figure 1). There were 12 total skid trails, each with one treatment and two replications. The skid trails were laid out in such a way that skidder traffic traveled west to east, and generally on a slight uphill grade (0%-10%) on all trails. The design also called for three trails to be laid out end to end from west to east, and this pattern was continued to the south until all 12 trails were laid out.

Traveling west to east, there was a 100 ft gap between the end of one trail and the beginning of the next. Traveling north to south, there was a 100 ft buffer from the centerline of one trail to the centerline of the next trail. All skidder traffic, other than the treatments, was confined to the area outside of the buffer zone and within the 100 ft gap between the end of one trail and the start of the next in order to preserve the area where the growth trees were located. A GPS unit was used to assist in the mapping of each skid trail in the study area.

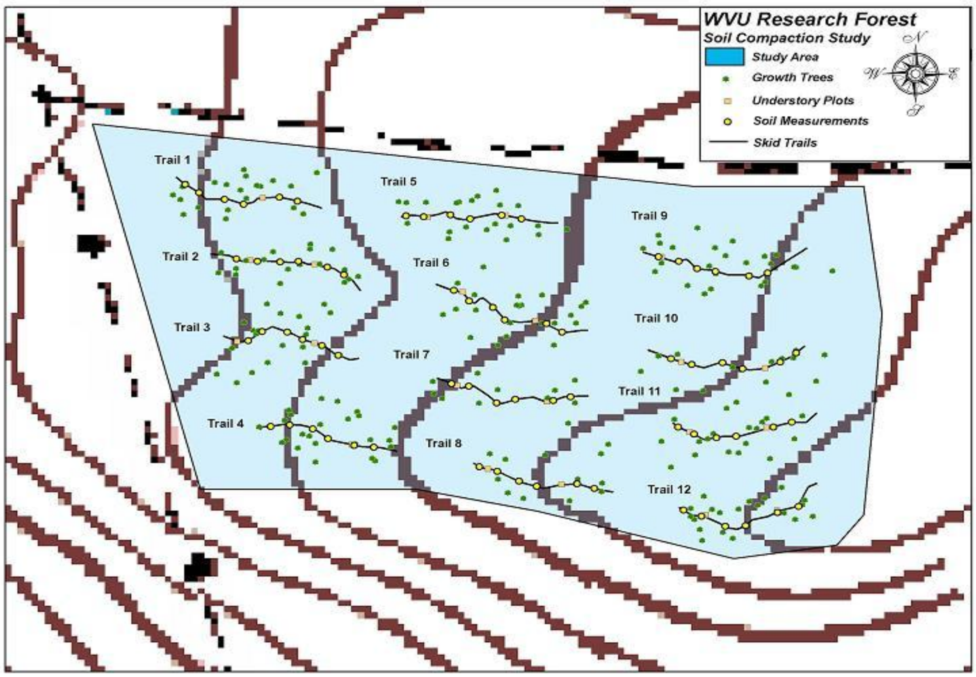

Figure 1. Skid trail layout, growth trees, understory plots, and soil measurement locations.

After the skid trails were laid out, a Caterpillar D3G tractor was used to clear the woody debris, standing understory trees, and some of the surface material (upper layer organic matter) from the skid trails in order to utilize the Troxler 3440 density and moisture gauge. No overstory trees were removed during the preparation phase. A John Deere 640G III cable skidder was employed for extraction operations with three levels of assigned loads: no load, ½ load, and full load. Full load was 798.6 board feet (BF) in Doyle Scale and was formed by four yellow-poplar long logs of 33 ft in length and varied in diameter while ½ load meant the skidder operated pulling two logs of 415.3 BF. No load meant that the skidder operated on the trails without any logs. The same two logs were used for the ½ load size during each cycle, and both were marked on the ends with high-visibility orange tree marking paint enabling distinct recognition.

2.2 Field Measurements

Understory sampling was conducted on two replications of each skid trail for a total of 24 sample locations. A 3'x12' cross section of the skid trail was laid out for each sample before any skidding activity took place. Regeneration and understory vegetation under 4' in height was counted by species within the sample area. A photograph was also taken of the plots for comparative purposes. A GPS unit was also used to assist in the mapping of each understory plot.

Trees were selected from the overstory canopy (dominant and codominant) on the basis of size and species. Only trees of sawtimber size were sampled (DBH 11.0 inches or above), and species were selected on the basis of local merchantability. Sample trees had canopies that were within 30 ft of the skid trail, and no more than five trees per replication per side of each trail were sampled. The total number of trees sampled was 225, giving an average of approximately 19 trees per skid trail.

Trees were labeled in a unique fashion with high-visibility, wet-coat orange tree marking paint based on the skid trail number, the replicate number, the tree number within the replicate, and the corresponding side of the skid trail when facing east. Tree measurements included species, diameter at breast height (DBH), total height, merchantable height in 8' sections, crown diameter, grade, distance from the side of the skid trail, and whether or not the tree was damaged during the skidding operation. All sample trees were measured for the past 10-years of growth by extracting a sample with an increment borer and then counting growth rings and measuring the cores in the lab. All increment boring was done on the southern side of the tree (azimuth = 180˚) and was restricted to approximately 2.5 inches in depth.

Each replicate within each skid trail was measured in two locations for initial soil density and moisture content for a total of 72 cross sections over the 12 skid trails. Soil measurements were made on a cross section of skid trail, starting 1' from the edge of the trail, and then every 2' across the 12' wide trail for a total of 6 measurements per cross section. The total number of initial soil density and moisture content measurements was 432. The measurements were made at a depth of 6" with a Troxler Labs 3440 soil density and moisture gauge. The cross sectional measurements were then averaged to calculate a cross sectional mean density and moisture content.

The nine skid trails that had undergone skidding treatments (skid trails 2, 3, 4, 6, 7, 8, 10, 11, and 12) were measured for post-treatment soil density and moisture using the same process as the initial measurements. A total of 54 cross sections (which were placed in the same initial measurement locations) were measured across the nine skid trails. The total of post-treatment soil density and moisture measurements was 324.

2.3 Data Analysis

A t-test was used to test if significant differences existed in bulk density changes. The general linear model (GLM) was applied to the data to examine the impacts of individual factors as well as their interactions on soil bulk density and moisture content in the skid trails.

$$Y_{ijk} = \mu + P_i + L_j + P_i * L_j + \varepsilon_{ijk}$$
$$i = 1, 2, 3$$
$$j = 1, 2, 3$$
$$k = 1, 2, 3$$

Where Y_{ijk} represents the k^{th} observation of the soil density or the soil moisture content and μ is the overall mean of the response variable. P_i is the effect of i^{th} number of machine passes (1, 3, and 5 loaded machine passes). L_j is the effect of j^{th} payload size (no load, half load, and full load). ε_{ijk} is an error component that represents all uncontrolled variability.

3. RESULTS

Greenbrier, red oak, and red maple were the most commonly found understory vegetation under 4 inches in height on the skid trails with a total number of 22, 20, and 17 per 100 ft^2, which accounted for 27%, 24%, and 21% of the total understory recorded, respectively (Table 1). Other understory included black cherry (7%), huckleberry (7%), chestnut oak (7%), and others (6%).

Table 1. Understory statistics in the skid trails before skidding.

	Black cherry	Chestnut oak	Greenbrier	Huckleberry	Red maple	Red oak	Others
#/100 ft^2	6	6	22	6	17	20	5
Percent (%)	7	7	17	7	21	24	6

Red oak (36%), yellow-poplar (24%), chestnut oak (19%), black oak (9%), scarlet oak (8%), and red maples (4%) were the major overstory canopy with less than 2% of other species recorded. The total average height ranged from 83 to 99 feet for the major species, with merchantable height of 32 to 58 feet (Table 2). Crown diameter averaged 32.25 feet ranging from 30.87 to 36.49 feet for the dominant and codominant trees measured. The average 10-year growth rate varied from 0.54 of an inch for black oak to about 1 inch for red maple. Average distance of these sampled trees to the centerlines of skid trails ranged from 13.95 to 19.28 feet.

Table 2. Statistics of sampled trees along the skid trails by species.

Species	THT (ft)	MHT (ft)	Crown Diameter (ft)	10-yr Growth (in)	Distance to Trail (ft)
Black oak	86.20	39.20	32.30	0.54	13.95
Chestnut oak	85.10	44.29	30.95	0.78	14.10
Red maple	86.11	35.56	32.22	1.00	21.22
Red oak	90.47	44.31	36.49	0.89	15.36
Scarlet oak	82.89	41.22	34.44	0.64	19.28
Yellow-poplar	98.66	58.42	30.87	0.89	17.55
Others	83.50	32.00	28.50	1.03	14.50

The DBH for the dominant and codominant trees sampled was between 12 and 25.6 inches with an average of 16.69 inches. Trees were categorized into six DBH classes: 14 (<=14 inches), 16 (>14 and <=16 inches), 18 (>16 and <=18 inches), 20 (>18 and <=20 inches), 22

(>20 and <=22 inches), and 24 (>22 inches). Heights, crown diameters, 10-year growth, and distances to the skid trail centerlines were summarized by DBH class (Table 3). The total height ranged from 84.10 to 97.76 feet and merchantable height varied from 36.62 to 54.33 feet as DBH changed from 14 to 24 inches. Crown diameter also increased from 27.88 to 41.31 ft. as the DBH changed from 14 to 24 inches. The average 10-year growth rate increased from 0.67 inches for 14 inches DBH class to 1.15 inches for 24 inches DBH class. Trees measured were located 15 to 24 feet away from the centerlines of skid trails.

Table 3. Statistics of sampled trees along the skid trails by DBH class.

DBH Class (in)	THT (ft)	MHT (ft)	Crown Diameter (ft)	10 yr Growth (in)	Distance to Trail (ft)
14	84.10	36.62	27.88	0.67	15.25
16	89.00	46.86	30.98	0.77	15.78
18	90.91	48.18	34.34	0.88	18.31
20	93.31	50.39	36.39	0.89	12.47
22	96.06	51.50	41.24	0.93	15.67
24	97.76	54.33	41.31	1.15	23.38

A t-test was used to test the statistical differences of soil moisture content and soil bulk densities between control and treated trails. Before extraction treatment, both soil moisture content (df = 430; t = 1.82; p = 0.0703) and soil bulk density (df = 430; t = -0.46; p = 0.6426) were not statistically different between control and treated trails (Table 4). However, both soil moisture content (df = 430; t = 10.84; p = 0.0001) and soil bulk density (df = 430; t = -6.95; p = 0.0001) differed significantly between control and treated trails after extraction treatment. The soil bulk density increased 9.4% from 69.50 lb/ft^3 before extraction to 76.05 lb/ft^3 after extraction.

Table 4. Soil moisture content and bulk density in control and treated skid trails.

	Treatment	Control	Treated	t-value	p-value
Moisture content (%)	Before	43.32	41.25	1.82	0.0703
	After	43.32	31.56	10.84	0.0001
Soil bulk density (lb/ft^3)	Before	69.50	69.94	-0.46	0.6426
	After	69.50	76.05	-6.95	0.0001

Table 5. Means and significant levels of soil bulk density and moisture content in skid trails[a].

		Moisture Content (%)	Soil Bulk Density (lb/ft^3)
No. of loaded machine passes	1	31.03A	75.45B
	3	33.20A	74.64B
	5	30.46B	78.05A
Payload size	no	37.81A	72.51B
	half	31.43B	74.48B
	full	25.44C	81.16A

[a] Means containing the same letter in a column of a group are not significantly different at the 5 percent level with Duncan's Multiple – Range Test.

Soil bulk density generally increased with the number of loaded machine passes and payload size. It increased 1.1, 6.2, and 8.9 lb/ft^3 after first machine pass with no load, half load, and full load compared to their initial bulk densities of 69.80, 68.25, and 71.80 lb/ft^3 in the skid trails without any machine passes, respectively (Figure 2). After three loaded machine passes, soil bulk density leveled out with these three payload sizes. The soil bulk density increased to 76.64, 73.86, and 83.64 lb/ft^3 after five passes for no load, half load and full load. However, the bulk density slightly decreased for the skidder with a half payload after five passes in comparison with the density after three loaded machine passes. Soil bulk density was not significantly different between after one pass and after three machine passes (Table 5). However, it increased significantly to 78.05 lb/ft^3 after five machine passes (F = 5.87; df = 2, 323; P = 0.0031). Similarly, the soil bulk density did not differ significantly between the with no load and the skidder with half payload. After five loaded machine passes, the bulk density for the skidder with a full payload differed significantly from the other two payload sizes (F = 38.13; df = 2, 323; P = 0.0001).

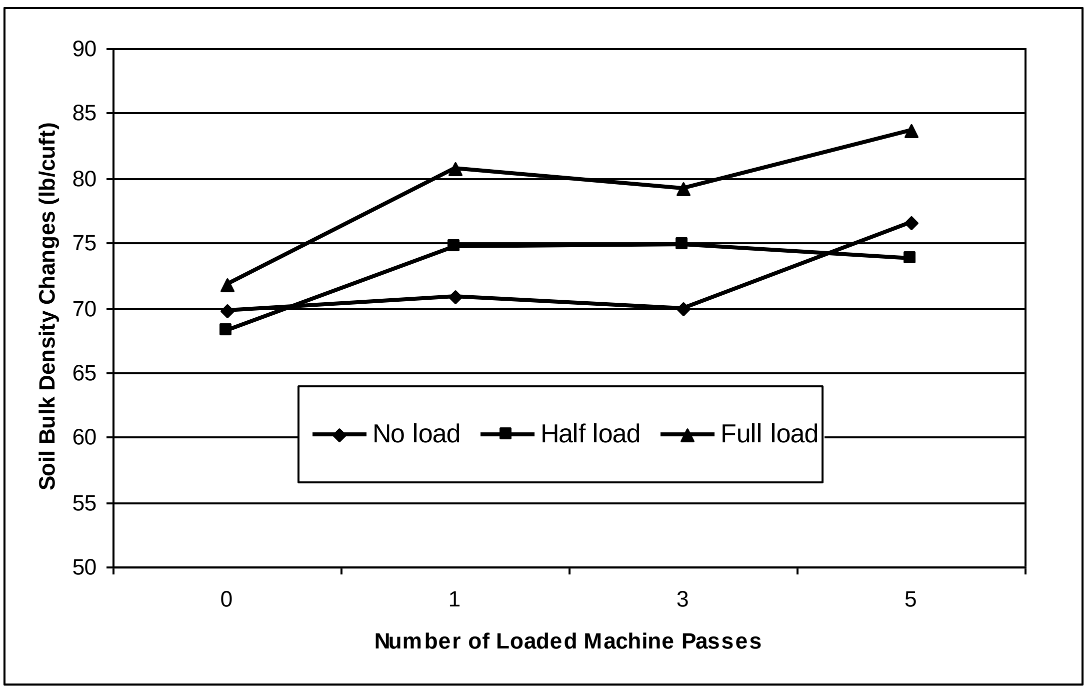

Figure 2. Soil bulk density changes by loaded machine pass and payload size.

4. DISCUSSION

Post-treatment soil bulk density increased as the number of loaded machine passes and the payload increased. The soil bulk density changes were significantly affected by the number of loaded machine passes and the payload size. The results from this case study also confirm that the majority of soil compaction in skid trails occurred after the first three passes of a loaded skidder (Greene and Stuart 1985, Wang et al. 2005). The small decreases in compaction measured after three or five passes were unlike most previously reported road compaction studies in which compaction generally has been reported to increase or remain constant with increasing numbers of passes. The decreases were recorded as rutting began to occur. When the formation of ruts appeared to stop, compaction began increasing again. Rutting may have created slight decreases in compaction by displacing soil to sides and out of the ruts, thereby acting like a stirring and aeration mechanism, resulting in less compact soil.

Our results support the recommendations of state BMPs to focus skidding to a few well developed preplanned designated skid trails and minimize trafficking across the general harvest area to protect soil (and water) resources. The findings from this study suggest that under certain conditions (1) most bulk density increase on skid trails occurs after the first three loaded machine passes, (2) preplanned skid trails may minimize bulk density increase across the overall site, and (3) emphasis should be placed on the amount of trail constructed through careful planning. Two follow-up measurements will be conducted at 3 years and 5 years post initial study, specifically to evaluate how soil compaction affects (1) residual stand growth by tree species, tree size, and the distance from tree to skid trail, (2) understory vegetation dynamics, and (3) compaction recovery.

5. ACKNOWLEDGEMENTS

The authors would like to thank Mr. Bob Driscole and Mr. Mike Boyce for their help during the field studies of this project.

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Riparian Management Zone width and its influence on stream characteristics following forest clearcutting: A case study of small streams in Japan*

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ABSTRACT: Unlike Washington State, Japan does not currently have timber harvesting regulations specifically applicable to riparian zones. If however, Riparian Management Zones (RMZs) were to be established in Japan and subsequent timber harvesting in these zones heavily restricted, the forest-based economy in Japan may worsen. In order to conserve an acceptable stream environment, as well as an economically viable forest industry, it is essential to examine the tradeoffs. These tradeoffs involve buffer strip width, an important component of RMZ design and management. The purpose of this study was to quantify the impact of undisturbed RMZ width as well as allowable length of clearcut area along the stream on: solar radiation, water temperature, algae biomass, and aquatic insect population levels. Measurements of these factors were taken at 200 meter intervals along the streams examined in this study. Stream A is located in an undisturbed forested watershed. An otherwise comparable stream B flows through a clearcut but is protected by a riparian buffer zone of 25 meters. Similar measurements were taken along three other streams. Stream C is also located within an undisturbed forest area, while stream D flows through a clearcut without benefit of a riparian buffer zone and stream E flows through a planting without benefit of a riparian buffer zone. A comparative analysis of streams A and B suggest that a RMZ of more than 25 meters in width might be desirable for reducing the environmental impact of clearcutting to an acceptable level. Contrarily, an analysis of streams C, D, and E supports an argument for felling areas within the RMZ of less than 25 meters and for planted areas within the RMZ of less than 75 meters. This study was supported in part by the fellowship of the Japan Forest Technology Association and by the Tanzawa Ooyama Synthetic Investigation in Kanagawa Prefecture, Japan.

Keywords: riparian management zone width, clearcutting, water temperature, aquatic insect, algae

1. INTRODUCTION

The riparian forest has several functions and among these are: interception of solar radiation, moderation of water temperature, provision of organic matter, and control of erosion (Nakamura. 1995). The riparian forest thereby conserves physical properties of the stream and its biodiversity.

In Washington State the establishment of Riparian Management Zones (RMZs) is one of the antecedents to active management of the riparian forest. This management includes banning

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 343-352.*

clearcuts within a "Core Zone". It also regulates clearcutting beyond the Core Zone but within an "Outer Zone" (Department of Natural Resources. 1997). Hence RMZ management decreases the influence of clearcutting around streams and maintains a habitat suitable for fish and the other organisms, both terrestrial and aquatic.

Unlike Washington State, Japan does not currently have timber harvesting regulations specifically applicable to riparian zones. If however, RMZs were to be established in Japan and subsequent timber harvesting in these zones heavily restricted, the forest-based economy in Japan may worsen.

In order to conserve an acceptable stream environment, as well as an economically viable forest industry, it is essential to examine the tradeoffs. These tradeoffs involve buffer strip width, an important component of RMZ design and management.

1.1 Objectives

The objective of this study was to compare, in a quantitative fashion, the impact of undisturbed riparian zone forest width and clearcutting on: solar radiation, water temperature, algae populations, and insect populations. In order to quantify these impacts, two investigative activities were conducted.

Research Activity 1. The quantification of RMZ impact comparing two streams; stream A, which is undisturbed, and stream B, flowing through an area which was clearcut except for a RMZ width of 25 meters on one side.

Research Activity 2: The quantification of the impact of clearcutting within the RMZ along three streams: an undisturbed stream C, a stream D along which the RMZ was removed by clearcutting on the left side, and a stream E, along which the forest was clearcut and replanted on both sides.

1.2 RMZ Width and Clearcut Removals within the RMZ

Figures 1 and 2 show the RMZ width and the permitted clearcut length in the RMZ. The RMZ width is measured perpendicularly from the stream edge on one side. This RMZ forest is expected to exert several positive impacts on stream properties as well as to decrease some of the negative impacts of felling on forest habitat. Allowable clearcutting along the stream edge comprises two distances, the entire length along one side of the stream and a specified length on the other side of the stream. The clearcut width within the RMZ is limited to the height of adjacent trees. This height ensures that the water surface will receive solar radiation leading to increased populations of algae and aquatic insects. At the same time, the limitation of clearcut area length along the stream may effectively restrict a detrimental rise in water temperature. Through setting RMZ width and permissible clearcutting lengths within the RMZ, it may be possible to maintain timber harvesting at acceptable levels while reducing the impacts of felling on the stream environment.

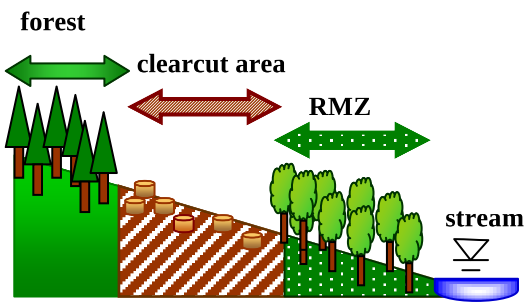

Figure 1.

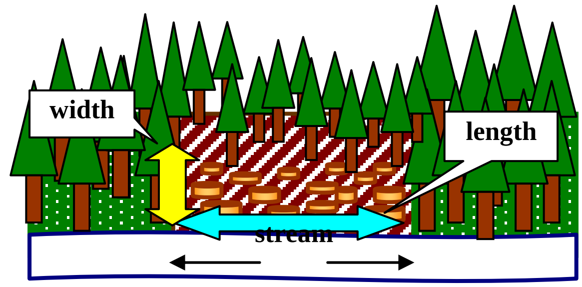

Figure 2.

2. METHODS

Factors measured included, under-crown solar radiation, water temperature, and population levels for algae and insects. Measurement procedures and locations were as follows.

Under-crown solar radiation: Under-crown solar radiation was measured at one minute intervals by a solar radiation recorder MDS/MkV/L (http://www.alec-electronics.co.jp). The sensor was set at a height of 1.5 meters and under the crown of a riparian tree near the stream. One measurement point was located along each of streams A, B, C, and E. On stream D 2 measurement points were taken, one within the forest area and a second in the clearcut area.

Water temperature: Water temperature was measured at hourly intervals by a Thermo Recorder Mini RT-30S (http://www.especmic.co.jp/). The sensor was set at 4 points with a 200m interval in streams A and B. In steams D and E, it was set at a 25m interval. Stream D had 8 recording points and stream E had 9 points. On stream C, it was set at 3 points with a 50m interval.

Algae biomass and aquatic insect level: The algae population level was measured as the dry algae weight on a 5cm ($25cm^2$) square placed on the surface of a stream rock (Aruga, *et al.* 2000). The aquatic insect population level was measured as a numerical count by genera, and species where possible, taken under stream rocks using a quadrat sample square of 25cm ($625cm^2$). These population measurement points were placed between measurement points for water temperature, and three samples were taken at each point.

2.1 Study Sites

Research Activity 1. RMZ width: In order to quantify the impact of RMZ width, research was done at two stream sites, A and B. Site A was an undisturbed stream, and site B was in a clearcut and planted area with a RMZ of 25 meters. These streams are tributaries of the Oomatasawa River in Kanagawa prefecture in Japan. Stream A's catchment area is 30.8 hectares and is 86% covered with Hinoki Cypress (*Chamaecyparis obtusa*). Stream B's catchment area is 69.9 hectares and is 68 % covered with Hinoki Cypress. The upper reaches of stream B, have 1.9 hectares planted to trees of 5 or 6 years. The lower reaches are located in a 1.4 hectare clearcut.

Research Activity 2. Allowable clearcutting length at RMZ: In order to quantify the impact of clearcutting length within the RMZ, the following three streams were investigated. Stream C is located in an undisturbed watershed. Stream D is without a RMZ and has a clearcut and planted area at its left side. Stream E, without a RMZ, flows through an area planted with trees of one or two years along both stream sides. These streams are tributaries of the Tenryu river in Shizuoka prefecture. Stream C's catchment area is 4.2 hectare and is forested with Hinoki cypress and Sugi pine (*Cryptomeria japonica*). Stream D's catchment area is 17.9 hectare forested with mainly Hinoki cypress and Japanese red pine (*Pinus densiflora*). Within this catchment there is also a 1.2 hectare clearcut and a 0.2 hectare planted area. Length of the clearcut area along stream D is 100 meters. Stream E's catchment area is 6.0 hectares and is forested with Hinoki Cypress and Sugi pine. This catchment also has 1.7 hectares of one or two year old trees. Length of the planted area along stream E is 125 meters.

3. RESULTS

3.1 Research Activity 1. RMZ width

Under-crown solar radiation: Figure 3 shows total daily global solar radiation and the corresponding under-crown radiation. Total daily global solar radiation tended to decrease from October 2004 to December 2004 while under-crown solar radiation during this same period had an increasing trend. The putative reason is that both of these streams flow through deciduous broad-leafed forests which are losing their leaves during this period. The under-crown solar radiation ofstream B was more than that of stream A during this period. However, in the month of October, during which the leaves of stream A and B's riparian forest didn't fall completely, the under-crown solar radiation of stream B was equal that of A. These data suggest that a RMZ of 25 meters intercepted solar radiation as well as the undisturbed forest cover of stream A.

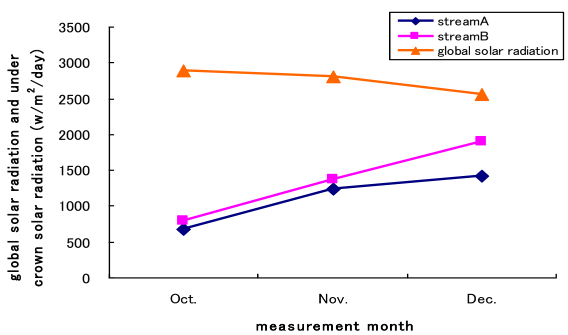

Figure 3

Daily maximum water temperature and diurnal range of water temperature: Figures 4A and 4B show daily maximum water temperatures and the diurnal ranges of water temperature for both streams from August 2004 through December 2004. August water temperatures tend to be the warmest observed during this period in both streams A and B. It is observed from the charts however that the water temperature rise between points 1 and 4 for both streams was not the highest during August. It was expected that the water temperature rise of stream B between points 1 and 4, where it flows through a clearcut, would be particularly noticeable. Unexpectedly, this increased temperature was not observed. It is inferred from this comparative analysis of water temperatures in streams A and B that a RMZ of 25 meters along stream B moderated the rise of its water temperature.

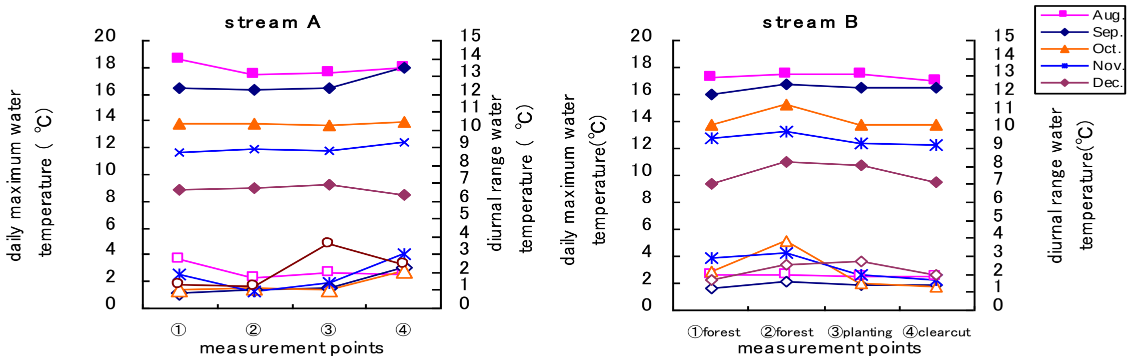

Figure 4

Algae biomass: Figure 5 shows algae biomass measured at various points along streams A and B. In stream A the biomass measured at the 3 points was essentially the same. For stream B, algae biomass in the planted and clearcut areas were both less than that found in the forested zone. Factors that have been identified as tending to decrease algae biomass are: decreasing solar radiation, increasing stream velocity and discharge levels, and increasing suspended sediment (Akimoto et al. 1986). Increased sediment loads were undoubtedly put into stream B from the clearcutting done 5 or 6 years prior to this study. It is hypothesized that the algae biomass decline observed in the planted and clearcut areas is due to this increased sediment load as well as increased stream velocity and discharge.

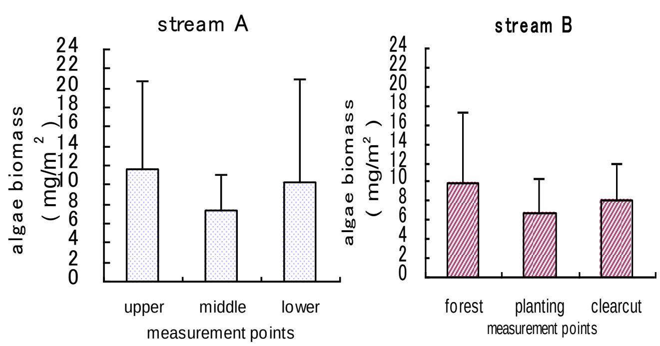

Figure 5

Aquatic insects: Figure 6 shows the number of species of aquatic insects at each sampling point of steams A and B as well as the total population count. Stream A had no significant difference in population count and number of species at the 3 sampling points. On stream B there was a decline in both species and total population count moving from forest, to planted area, to clearcut. Factors that tend to decrease aquatic insect population levels and diversity are increasing stream velocity and discharge and increasing sediment load. The sediment load is particularly important as it covers interstitial space between stones in the stream bed (Takemon 1998). Reduced habitat availability and quality negatively impact the aquatic insect biota. A comparison of the planted and clearcut areas shows that the negative impact was greater in the clearcut, both in terms of total population and number of species. Hence, it is hypothesized that immediate replanting after a clearcutting operation has the potential to reduce sediment loads after harvest. Consequently it is proposed that a RMZ of more than 25 meters in width is needed or immediate replanting should occur. These remedies might be judged suitable for reducing the environmental impact of clearcutting to an acceptable level based on stream B observations.

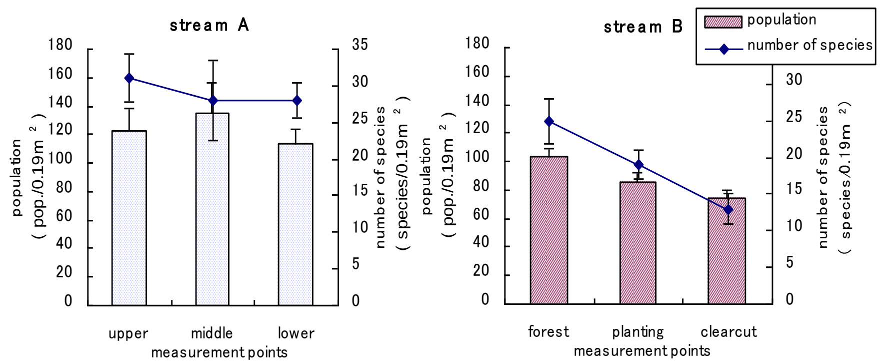

Figure 6

Discussion: Data of under-crown solar radiation and water temperature shows that a RMZ width of 25 meters effectively moderates solar radiation and water temperature. From this perspective it appears that a RMZ width of 25 meters effectively buffers these effects associated with clearcutting. On the other hand, algae biomass and aquatic insect population numbers and species all tend to decrease in both planted and clearcut areas. The impact on aquatic insects was particularly significant. It was not possible however to conclude that decreasing levels of algae and aquatic insect populations were due to clearcutting. It is necessary to investigate in more detail the origin of the suspended sediment in order to determine what percentage comes from the upper stream, the clearcut and the planted area.

3.2 Research Activity 2. Allowable clearcutting length in the RMZ

Under-crown solar radiation and solar radiation at clearcut area: Figure 7 shows under-crown solar radiation and solar radiation in the clearcut area from July through December. Under-crown solar radiation within the forest area of streams C, D, and E ranged between 50 w/m^2/day and 600 w/m^2/day during this period. Solar radiation in the clearcut area ranged between 660 w/m^2/day and 2500 w/m^2/day. These data show that solar radiation reaching the water surface in the clearcut area is 12 times higher than that within the forest area of stream D.

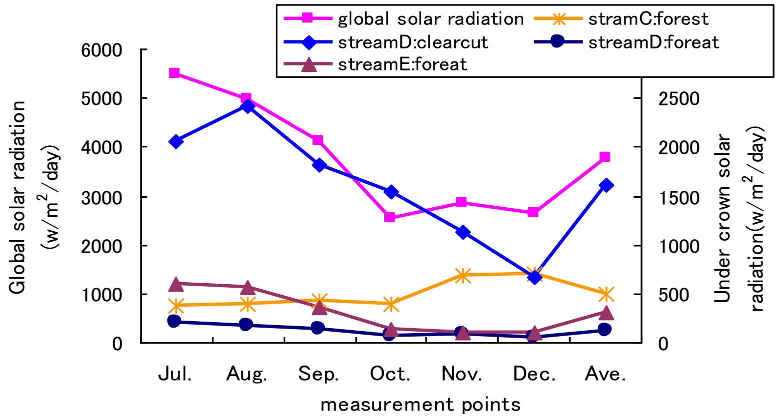

Figure 7

Daily maximum water temperature and the diurnal range in water temperature:

Figure 8 shows daily maximum water temperature and diurnal range of the water temperature from July through December. A major determinant of allowable clearcutting length in the RMZ is its impact on daily maximum water temperature. This temperature reaches its maximum between July and August. There is a relationship between stream water temperature and feeding activity of Yamame (*Oncorhynchus masou*), a Salmonid. Feeding activity of Yamame occurs when the water temperature is between 18 and 22ºC. Water temperatures between 24 and 26ºC place it in a feeding stasis, and over 26ºC feeding is entirely halted (Sato et al. 2001).

Daily maximum water temperatures in stream C ranged between 20.1 and 21.4ºC, meaning that stream C was cool enough to keep feeding activity brisk. In stream D however, daily maximum water temperature rose to 24.8ºC when it flowed through a clearcut area of only 25 meters, which would place Yamame in a state of feeding stasis. In stream E, daily maximum water temperature rose to 24.2ºC when it flowed through a planted area of 75 meters, which also implies a feeding stasis. An analysis of streams C, D, and E supports an argument for keeping the clearcut area within the RMZ to less than 25 meters in stream D, and an argument for keeping the planted area within the RMZ to less than 75 meters in stream E.

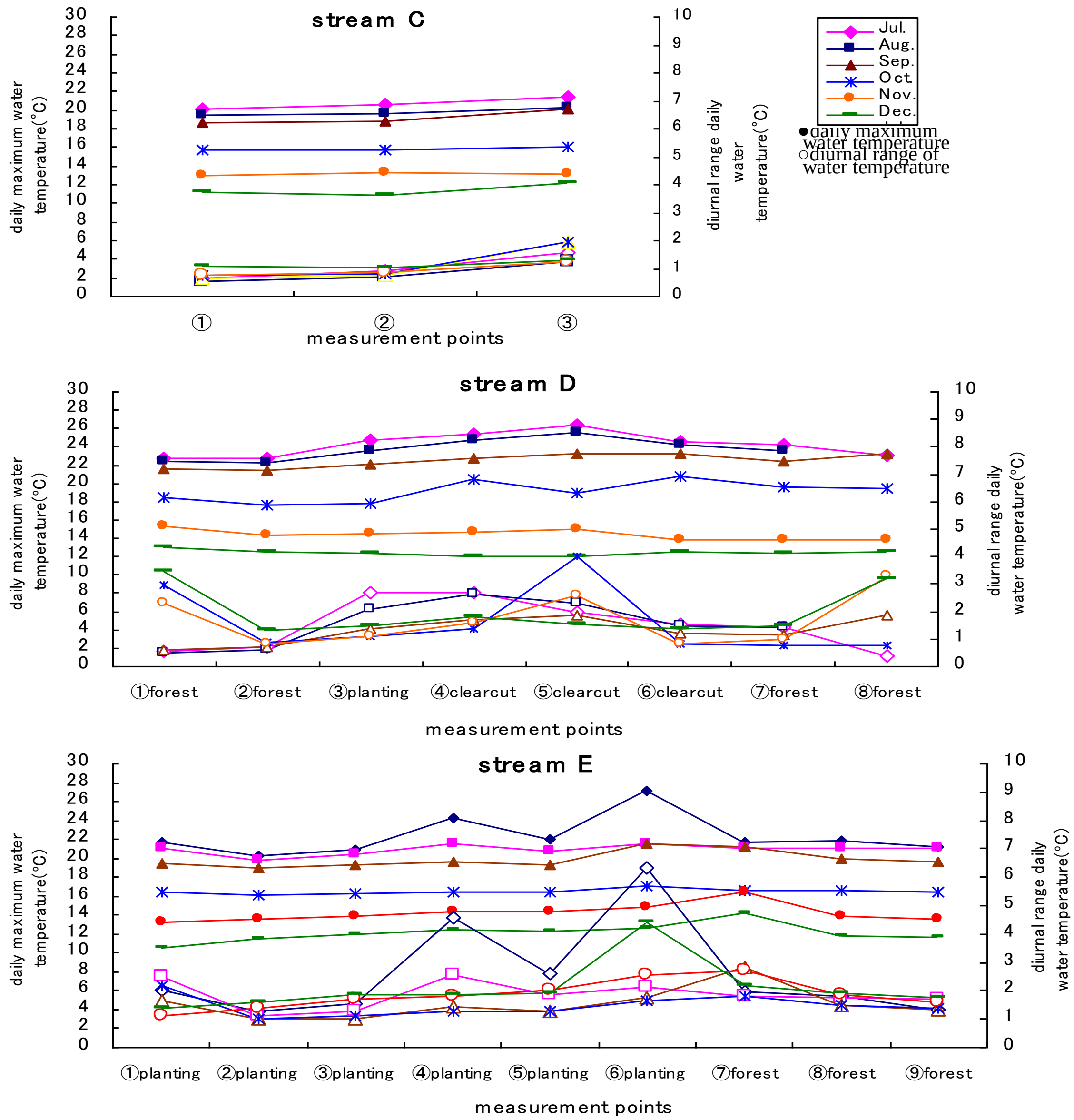

Figure 8

Algae biomass: Figure 9 shows the average algae biomass of streams C, D, and E. Figure 10 shows algae biomass at each measurement point in streams C, D, and E. Comparing average algae biomass, it is noted that streams D and E have higher levels than C. It was therefore presumed that RMZ conditions that include clearcuts and planted areas increased algae biomass. Algae biomass of the clearcut area were more than that of the forest area of stream D. If there are clearcut areas in upper stream reaches the algae biomass of lower forested areas is higher than the upper forestedarea. These data support the hypothesis that stream environments with a lot of solar radiation, such as that provided by clearcuts, tend to have higher algae biomass.

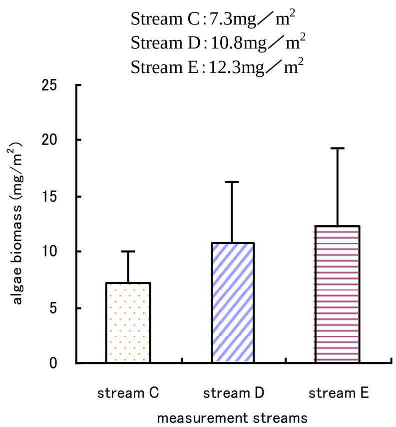

Figure 9

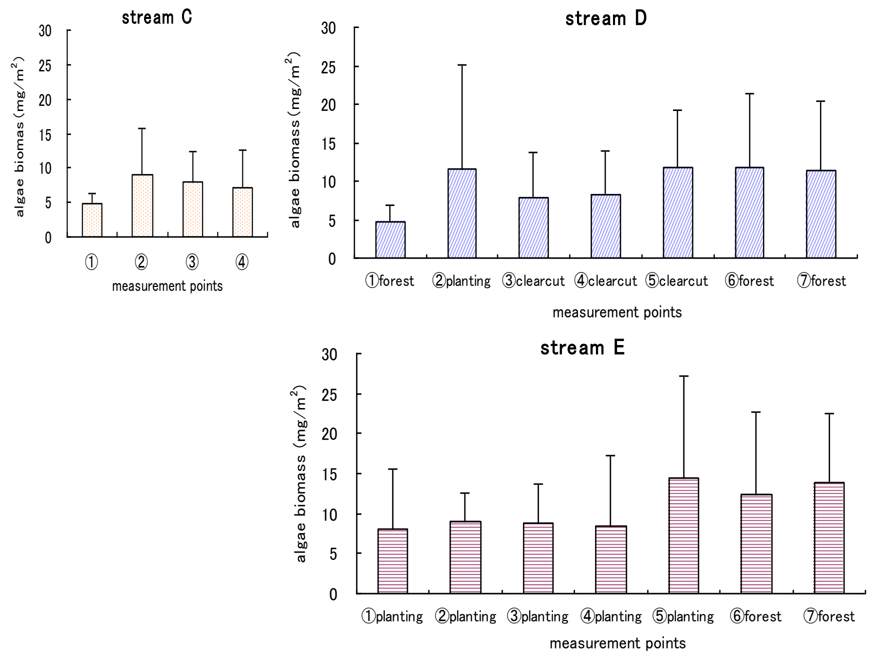

Figure 10

Aquatic insects: Figure 11 shows the total population size and number of species of aquatic insects of stream C, D, and E. Figure 12 shows these measurements at different points along streams C, D, and E. The population size was highest in stream E, and the number of species was highest in stream C.

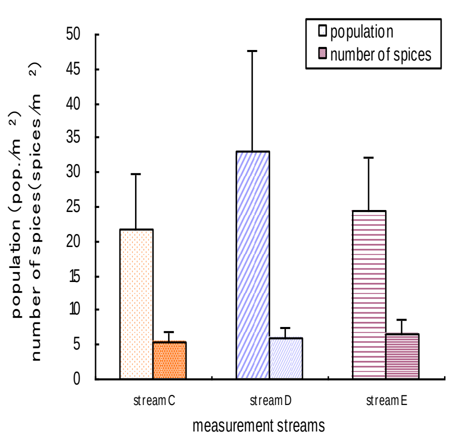

Figure 11.

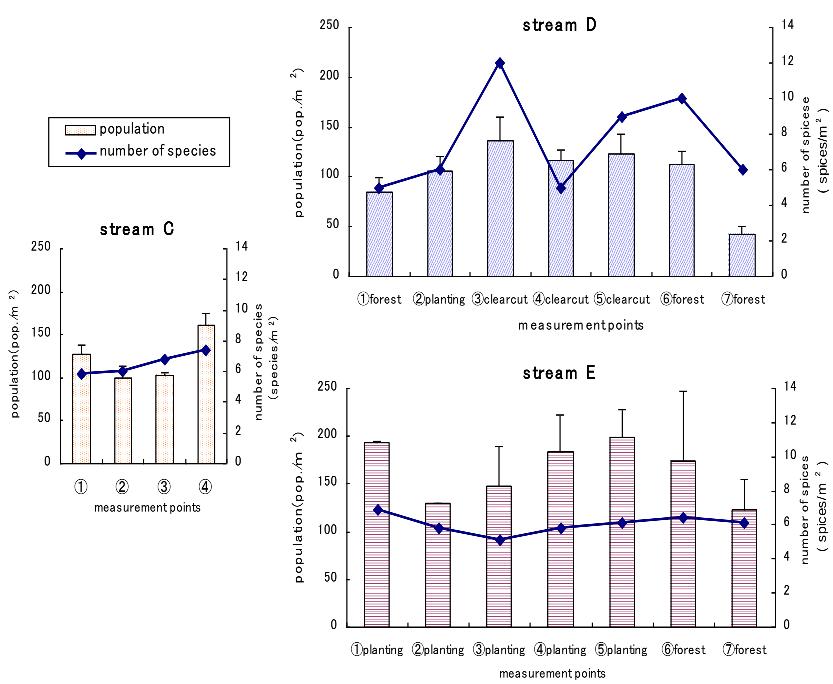

Figure 12.

Upon comparison of the various measurement points, it is noted that both population size and number of species tend to increase with planted and clearcut area. This observation supports the idea that RMZs with clearcut and planted areas have both larger populations and higher diversity of aquatic insects. In stream D the clearcut area in the RMZ tends to increase the population of aquatic insects during ordinary water discharge. In the case of heavy rainfall however, there is some fear that the population size and diversity of aquatic insects will decrease as a consequence of sediment flow from the clearcut area into the stream.

Discussion: A comparison of solar radiation reaching the water surface within the clearcut area of stream D and that of a forested area shows 12 times more radiation within the clearcut. The allowable clearcutting length within the RMZ were quantified by examining the relationship between daily maximum water temperatures in streams C, D, and E with the feeding activity of Yamame. As a result of this examination it is suggested that clearcut areas within the RMZ should be less than 25 meters and planted areas less than 75 meters. These limits on clearcut and planted areas should maintain stream water temperatures which encourage feeding activity. These limits will also create a stream environment that promotes healthy levels of algae biomass and aquatic insect populations.

4. CONCLUSION

This study quantified the impact of undisturbed RMZ width as well as allowable clearcutting length in the RMZ. The undisturbed stream environment was evaluated and compared with the influence of clearcutting on physical and organic factors. This is an important step toward developing and evaluating a RMZ tradeoff model that varies buffer width and harvesting intensity with different levels of water resource protection.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Does a consumer GPS receiver achieve submeter accuracy under forest canopy?*

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Abstract
It is known that high-end GPS receivers work better under forest canopy than consumer GPS receivers. However, higher costs of them are a major obstacle for forest owners and managers to utilize them for forest management. For this reason, we should make more use of consumer GPS receivers by overcoming difficulties in getting better positional accuracy under forest canopy. The objectives of this study are to determine positional errors of a consumer GPS receiver under forest canopy and to clarify the conditions and requirements to achieve submeter accuracy using a consumer GPS receiver. Therefore, in this study, we conducted field experiments of GPS positioning with different methods of data correction (code-phase and carrier-phase DGPS) and periods of data collection (2 to 300 minutes). The GPS receiver used in this study was Earthmate USB GPS (DeLorme) that is capable of receiving L1 carrier-phase data and generating Rinex files. These files were differentially corrected by using GPS PostPro 2.0 (DeLorme), which is capable to output only float solutions for carrier-phase data. The results showed that positional errors were unstable and unpredictable when code-phase DGPS was used. In addition, there was no relationship between positional errors and periods of data collection. On the other hand, it was found that positional errors were smaller with increasing periods of data collection when carrier-phase DGPS was used, and that sub-meter accuracy was achieved under forest canopy when the period of data collection was 300 minutes. We also used three different base stations for data correction with different distances from the remote station (2 to 234 km). As a result, relatively large positional errors were sometimes produced for carrier-phase DGPS when the distance between the remote station and base station was 234 km.

1. INTRODUCTION

It is known that forest canopy adversely affects positional accuracy of GPS positioning due to signal attenuation, and this has been a major obstacle of GPS utilization for forest management. Therefore, many studies have been conducted to determine the performance of GPS positional accuracy under forest canopy. Martin et al. (2001) evaluated DGPS positional accuracy and precision on Irish forest roads with typical peripheral canopies and discussed the relationship between position dilution of precision (PDOP) and the percentage of open sky. This study also showed that both DGPS accuracy and precision improved with decreasing peripheral obstruction. Næsset (1999) showed that the accuracy of GPS positioning was significantly higher with the 12-channel GPS receiver than with the 6-channel GPS receiver and was significantly higher with the combined use of the C/A code and carrier phase than with the use of

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 355-362.*

the C/A code only. Kobayashi et al. (2001) evaluated five GPS receivers' performance by comparing the positional accuracy of the autonomous GPS, real-time DGPS, and carrier phase GPS. Results indicated that the autonomous GPS and real-time DGPS produced positional errors of 15.4–48.6m and 2.7–21.7 m, respectively, which were based on the condition that SA was on. Sawaguchi et al. (2001) discussed the effect of stand conditions on positioning precision with real-time DGPS and found factors that affected positional precision by using multiple regression analysis. Mori and Takeda (2000) showed the effects of SA removal on positional accuracy of the DGPS. In most of these studies, high-end GPS receivers that work well even under forest canopy were used, but they often cost too much for forest owners and managers in Japan, who are struggling with the difficult market environment. In fact, high-end ones often cost more than 3,000 USD while consumer GPS receivers cost only 100-500 USD. For this reason, we should make more use of consumer GPS receivers by overcoming difficulties in getting better positional accuracy under forest canopy. The objectives of this study are to determine positional errors of a consumer GPS receiver under forest canopy and to clarify the requirements to achieve submeter accuracy using a consumer GPS receiver. Therefore, in this study, we conducted field experiments of GPS positioning with different methods of differential correction and periods of data collection. We also used three different base stations for differential correction with different distances from the remote station.

2. MATERIALS AND METHODS

2.1 GPS and software

The GPS receiver used in this study was Earthmate USB GPS (DeLorme) (Figure 1) that is capable of receiving L1 carrier-phase data and generating Rinex files for differential correction. Moreover, this GPS receiver is characterized by its small size (1 7/8" wide by 2 3/32" long), fast signal acquisition (in under 45 seconds), USB connection without external batteries, WAAS capability, 12 channels, NMEA compliance and low-power consumption. The GPS data collected with this GPS receivers were differentially corrected by using GPS PostPro 2.0 (DeLorme), which is capable to output only float solutions for carrier-phase data. This software provides an array of tools for working with Rinex files, single carrier phase processing for static baselines, code (DGPS) processing for dynamic baselines, automatic correction against CORS reference stations, or against a second stationary Earthmate USB GPS, an intuitive wizard interface through the post processing steps, satellite prediction tools for data collection mission planning and a detailed report of the post processed results. This software calculates the coordinates as float solutions for carrier-phase DGPS. The price of Earthmate USB GPS including GPS PostPro 2.0 is approximately 300 USD.

Figure 1. Earthmate USB GPS (DeLorme).

2.2 Field experiments

We conducted field experiments inside the forest of the Kamigamo Experimental Station, Field Science Education and Research Center, Kyoto University on February 23 to 25, 2006. Earthmate USB GPS was set up at three points, that is, K2, A5 and A8, inside the forest. K2 was located in a forest glade on the top of the hill with good visibility of GPS satellites. A5 was at the side of a forest road on the top of the hill, and was surrounded by natural forest stands consisting of Japanese cypress (*Chamaecyparis obtusa*) and broad-leaved species with a thick shrub layer. A8 was at the side of a forest road on the hillside under closed canopy of Japanese cypress (*Chamaecyparis obtusa*). Figure 2 shows fisheye photos taken at these points.

Figure 2. Fisheye photos taken at K2 (left), A5 (center) and A8 (right).

At each point, GPS measurements were conducted for 300 minutes as shown in Table 1. We started each GPS measurement four minutes earlier on the next day because the same constellation of GPS satellites appears four minutes earlier day by day. Figure 3 shows the number of visible GPS satellites during the field experiments. In this study, horizontal positional errors were calculated and compared in terms of accuracy, which refers to the closeness of the sample mean to the true value (Leick 1995) and was calculated according to Yoshimura and Hasegawa (2003).

Table 1. Schedule of the field experiments.

Date	Point	Antenna height (m)	Starting time (JST)	Ending time (JST)
February 23, 2006	K2	1.69	10:24:00	15:23:59
February 24, 2006	A5	1.41	10:20:00	15:19:59
February 25, 2006	A8	1.41	10:16:00	15:15:59

JST, Japan Standard Time (UTC+9 hours).

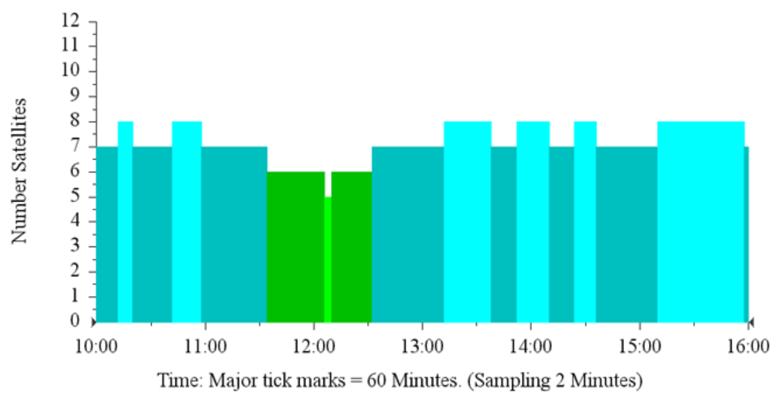


Figure 3. Number of visible GPS satellites during the field experiments.

2.3 Data processing

The GPS data collected on each day were differentially corrected using the data of the first 2, 5, 10, 30, 60, 120 and 300 minutes with two methods of differential correction, that is, code-phase and carrier-phase DGPS to clarify the effects of methods of differential correction and periods of data collection on positional accuracy. In addition, we used three different base stations for differential correction with approximate distances of 2, 15 and 234 km from the remote station to clarify the effects of distance between the remote and base stations on positional accuracy.

3. RESULTS AND DISCUSSION

Tables 2 and 3 show positional errors calculated for code-phase and carrier-phase DGPS, respectively. The base station used for this calculation was the one that was at a distance of 2 km from the remote station. As shown in Table 2, longer elapsed time of measurements did not always produce better positional errors. Instead, it can be seen that positional errors became worse for 60 – 120 minutes of elapsed time at K2 and A8 and for 5 – 10 minutes of elapsed time at A5. It should be also noted that positional errors at A5 were much larger than those at K2 and A8. Obviously, there were multipath errors in the data collected at A5. As a result, it was found that positional errors for code-phase DGPS were unstable especially under forest canopy due to possible effects of multipath. Table 3 shows that there was not a great difference in positional errors between code-phase and carrier-phase DGPS, but positional errors at A5 that were affected by multipath did improve steadily as elapsed time of measurements advanced. It should be also noted that submeter accuracy was achieved at all three points after 300 minutes of elapsed time of measurements.

Table 2. Positional errors for code-phase DGPS (m).

Point	Elapsed time (min)						
	2	5	10	30	60	120	300
K2	3.22	1.84	1.51	0.89	0.67	1.45	0.93
A5	30.69	15.42	107.90	40.33	19.28	13.75	6.82
A8	1.57	1.23	1.70	0.88	0.56	1.96	0.83

Table 3. Positional errors for carrier-phase DGPS (m).

Point	Elapsed time (min)						
	2	5	10	30	60	120	300
K2	1.40	0.79	1.11	1.05	1.53	1.60	0.55
A5	25.37	20.46	9.82	5.74	2.79	1.43	0.67
A8	3.99	2.66	2.13	2.05	2.57	2.22	0.90

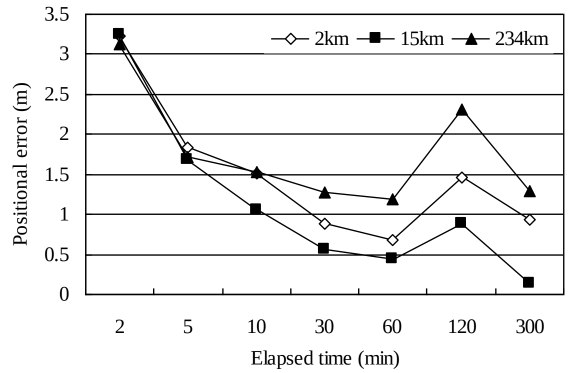
Figures 4 and 5 show positional errors according to the distance between the remote station and base stations for code-phase and carrier-phase DGPS, respectively. As shown in Figure 4, there was not a great difference in positional errors according to the distance between the remote station and base stations for code-phase DGPS. On the other hand, there were relatively large positional errors for carrier-phase DGPS when the distance between the remote and base stations was 234 km (Figure 5). It should be noted that longer elapsed time of measurements such as 120 or 300 minutes may have eliminated such a distance effect. As a result, it is recommended to conduct GPS measurements for longer time when the base station is not closely located from the remote station.

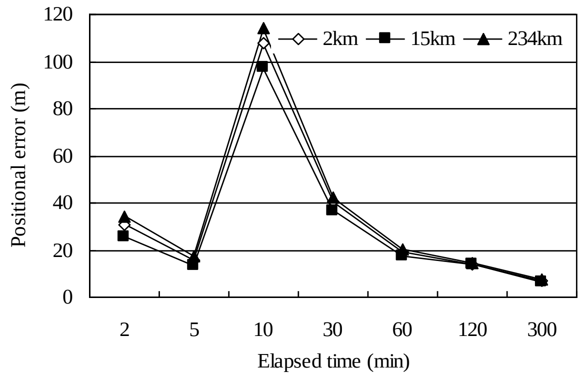
4. CONCLUSIONS

In this study, submeter accuracy was achieved under forest canopy by using Earthmate USB GPS, but it was not done constantly. For one reason, consumer GPS receivers such as Earthmate USB GPS are influenced by multipath effects more easily than high-end GPS receivers that sometimes use multipath rejection technology. In fact, there were multipath errors seen in the data collected at A5, and positional errors for code-phase DGPS were unstable especially under forest canopy due to possible effects of multipath. On the other hand, carrier-phase DGPS with GPS PostPro 2.0 eliminated such negative effects, and submeter accuracy was achieved at all three points after 300 minutes of elapsed time of measurements. As for the distance between the remote and base stations, it is recommended that GPS measurements should be conducted for longer time such as 120 or 300 minutes only when there are not available base stations closely located from the remote station. In conclusion, requirements to constantly achieve submeter accuracy under forest canopy are:

- To use Earthmate USB GPS and GPS PostPro 2.0
- To use carrier-phase DGPS for differential correction
- To conduct GPS measurements 300 minutes or more
- To use a base station up to 234 km from a remote station

Of course, GPS measurements for 300 minutes are not practical especially when there are many coordinates of points to be determined. Alternatively, to achieve positional accuracy up to 3 m, GPS measurements can be conducted for only 5 minutes, but a base station up to 15 km from a remote station must be used for carrier-phase DGPS.





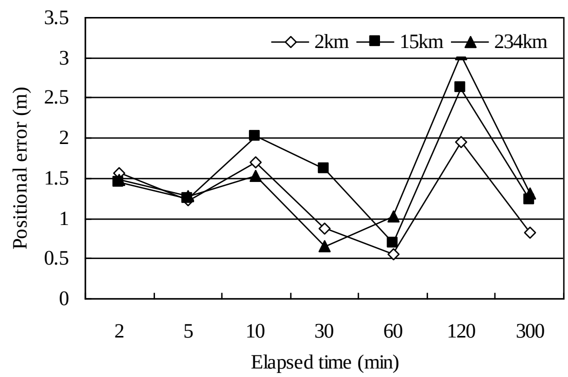
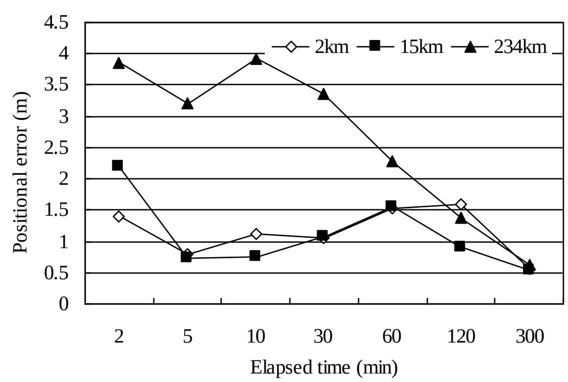
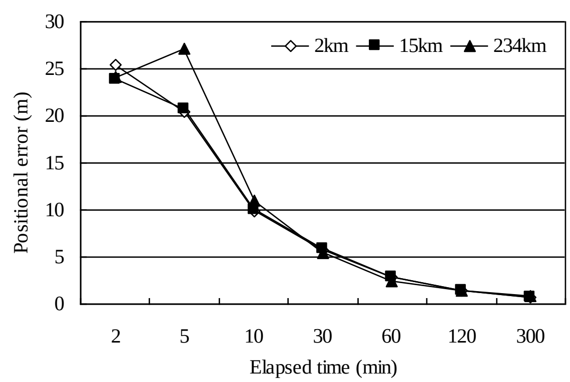


Figure 4. Positional errors for carrier-phase DGPS according to the distance between the remote station and base stations at K2 (upper left), A5 (upper right) and A8 (lower left).





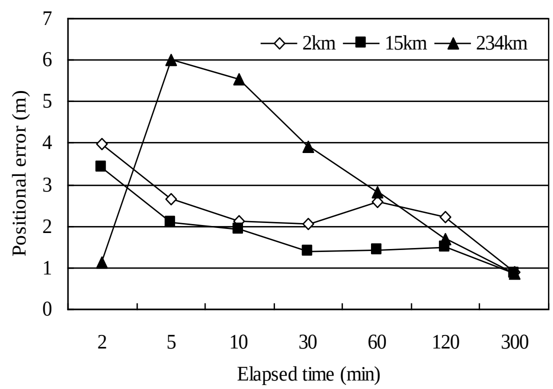


Figure 5. Positional errors for code-phase DGPS according to the distance between the remote station and base stations at K2 (upper left), A5 (upper right) and A8 (lower left).

5. ACKNOWLEDGEMENTS

The authors would like to thank Dr. Mitsuhiro Nose for his helpful assistance during the field experiments.

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Developing an Annual Harvest Operations Planning Model for Turkish State Forest*

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Abstract
Sustainable management of forest resources requires doing planning for all forestry operations such as harvesting etc. Hierarchical planning approach consisting of strategic, tactical and operational level is an efficiently way for integrated forest planning problems. In this concept, harvest operations can be planned in tactical and operational level. Tactical harvest plan may be equivalent to forest management and silviculture plans. Operational harvest plan is also short-term and detailed, which can encapsulate range from daily to two years planning period. As well, harvest planning is inherently a complex task because of economical, technical, environmental, and socio-economical objectives and constraints. Thus, to optimize decisions on harvest planning for example in Turkish Forestry System, it was developed an Annual Harvest Operation Planning (AHOP) model based on annual budget for 12 and/or 18 months harvesting decisions. In this study, it was aimed to introduce AHOP methodology to display that how the AHOP model had been set up for state forestry, which planning steps had been followed, how operational decisions had been optimized, how model results could have been adapted to real application problem and what the probable advantages obtained from solving of test problem was. The planning model includes the steps that (1) (spatial) database projection, (2) technical and topographical analysis, (3) cost analysis, (4) modeling of operational decisions, (5) solution, (6) synthesis, and (7) operation schedule and/or plan. In this planning context, it was used GIS for the first and second steps. Cost analysis was carried out by standard calculation methods via available equation. For fourth and fifth step, it was used Linear and Mixed Integer (linear) Programming for optimization of operational decisions in this planning manner. AHOP methodology could pan out to successfully use of time, money, work and machine force for optimal harvesting operations in the test problem.

Keywords: annual harvest planning, operational planning, LP, MIP, optimization, hierarchical planning

1. INTRODUCTION

The total area of Turkey is 77.056.192 hectares and approximately 27 % of this area is forests. In Turkey, in the past 15 years an annual average of 7 million m³ of industrial wood and 9 million m³ of firewood have been produced. The majority of total forestland (99,9 % of) belongs to Ministry of Forestry. One of the most significant features that separates Turkish forestry from the forestry in western countries is the presence of 18.358 forest villages living 8,5

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 363-374.*

million persons, either within the forest or at the edge of the forest. The forest villagers compose 49,5% of the rural population. For all that, the forestry sector takes place among the most employment provider (13 million man/day per year). Turkish constitution, Forestry Law, and Regulations dictate that forest villagers ought to be worked in harvest operations. Therefore, general means of subsistence of 300.000 villagers are provided from forest operation workmanship (ÖİKRT, 2005). The harvest and the other forestry operations are executed by forest cooperatives consisting of forest villagers, as monopoly by traditional methods disregarding of mechanization and without any analytical harvest planning conception (Bayoğlu, 1996; Eker, 2004)

The timber harvesting expenditures capture the majority of the total forestry expenditures per unit costs that amounts to 35 percent of total expenditures, which is highly proportion. (Eker and Acar, 2002). Furthermore, when harvest operations are carried out, various environmental impacts occur in residual stand, soil, and water resources. It can also be done a quality and quatity losses in forest products to being harvested (Gürtan, 1975; Acar, 1994).

Harvest planning bases on decennial forest management plans and quinquennial silvicultural prescriptions or detailed plans, in Turkey. The planning decisions are for mid-time horizon. The annual allowable cut (AAC) is estimated with respect to thinning and final felling to maximize total harvested volume and value, on a 10-year time horizon. Forest management plans are prepared to each planning unit that is application area of state forest enterprises and enumerate harvesting blocks to be harvested in each year within planning horizon. The main objective of the management plan is typically to maximize net present value.

In one year time horizon, it is prepared harvesting programs for harvesting operations. These programs are designed to balance the annual budget and to supply annual or monthly wood demands. But, these programs cannot describe harvesting time and schedule of block to be harvested and allocate harvesting system types and crews within one year.

This situation indicates that the annual harvest planning strategy is necessary for Turkish State Forestry. This planning strategy should offer a consistent plan that is applicable as technically, profitable for economically, and acceptable for environmentally and socially. Therefore, an AHOP methodology was developed to achieve annual planning objectives. But, the planning of forest harvesting activities is a complex task requiring integration of technical/topographical, economical, environmental, and social-institutional factors. This planning problem is one of the most important issues in forest resources management.

Forest harvest planning was generally dealt with in hierarchical planning approach (Robak, 1984; Weintraub and Cholaky, 1991; Gunn, 1991; Epstein et all., 1999; Laroze and Greber, 1991; Martel et all, 1998), which is three levels as strategic, tactical, and operational. Short-term harvest operation planning was generally inserted into operational planning level But, when the scope of the harvest operations planning could be enlarged and it was taken into consideration in tactical planning level (Karlsson et all., 2002; Dykstra ve Heinrich, 1996). Especially, planning horizon, planning area and planning objectives have changed to place and level of harvest planning.

The planning problem mentioned in this paper is annual harvest operation planning (AHOP) problem. AHOP means that planning of; which harvesting unit/block is to be harvested in each planning season/period, which harvesting system is to be used to harvest, how many harvesting crew is to be employed, which forest roads are to be used, where harvested assortments are to be transported to which state forest storage. AHOP corresponds to 12 or maximum 18 months harvesting, in a forest district. This planning method is affected from technical-topographical conditions, economic limitations, environmental restrictions, and social-institutional expectations. However, AHOP problem is considerably complex because of including versatile goals and constraints (Eker, 2004).

To solve complex harvest operation planning problem, it was used macro (10 years) and micro (1 year) level transportation planning method based on harvesting system selection to physical/topographical conditions of harvesting area (Bayoğlu, 1972; Acar, 1994). As considerable as physical dimension of harvest operation planning, its economical dimension is important, as well. Therefore, to optimize as economically harvest plans, it was used mathematical-statistical methods and productivity-cost analysis functions. But, conventional evaluation techniques connected with economy were disqualified for harvest planning problem (Reimer, 1979). For that reason, it was eventually used operations research that is quantitative decision support systems (Oborn, 1996). When published a bibliography on operations research in forestry by Martin and Sendak (1973), it was referenced that 45 items OR techniques had been used to make a decision on forestry planning for harvesting and 28 items for timber transport. In addition, Schuster et al. (1993) quoted that there were many computer programs based on dynamic, linear (LP), integer (IP), and mixed integer programming (MIP), network analysis, heuristic process, simulation, Monte Carlo, artificial intelligence /expert systems, etc modeling techniques. Recently, many harvest operation planning model have been developed relevant to all of harvesting process or a part of the process such as logging, hauling, or skyline route planning (Rönnqvist et all, 1999; Shemwetta, 1997; Chung and Sessions, 2000). Additionaly, it was preferred qualitative decision tools like AHP (Engür, 1996; Saaty, 1989) and knowledge based system (Lan, 2001), in order that some qualitative criteria could be added to decision process of the harvest planning.

In this study, it was aimed to introduce the conceptual framework of AHOP methodology to display that how the AHOP model had been set up for state forestry, which planning steps had been followed, how operational decisions had been optimized, how model results could have been adapted to real application problem and what the probable advantages obtained from solving of test problem was.

2. METHODOLOGY OF AHOP MODEL

It is benefited from transportation planning (Bayoğlu, 1996; Acar, 1994), and hierarchical planning concept (Weintraub and Cholaky,1991; Gunn, 1991) to develop AHOP methodology, consisting of mainly three module that are; (1) Setting up database system and technical-topographical analysis, (2) Cost analysis of harvesting systems, and (3) Modeling of operational decisions, solutions, synthesis, and plan draft (Eker, 2004).

2.1. Database System and Technical Analysis

In the first module of the AHOP model, it is followed steps mentioned below (Figure 1).

1. A spatial database system is firstly designed by means of GIS, which should include topographical, stand, road network, and geology maps and georeferenced information relevant to their attributes. Harvesting compartment to be harvested in planning horizon is flagged. Information about each compartment such as standing volume, silvicultural

prescription, tree species, and background in previous plan horizon, are added to GIS database system.

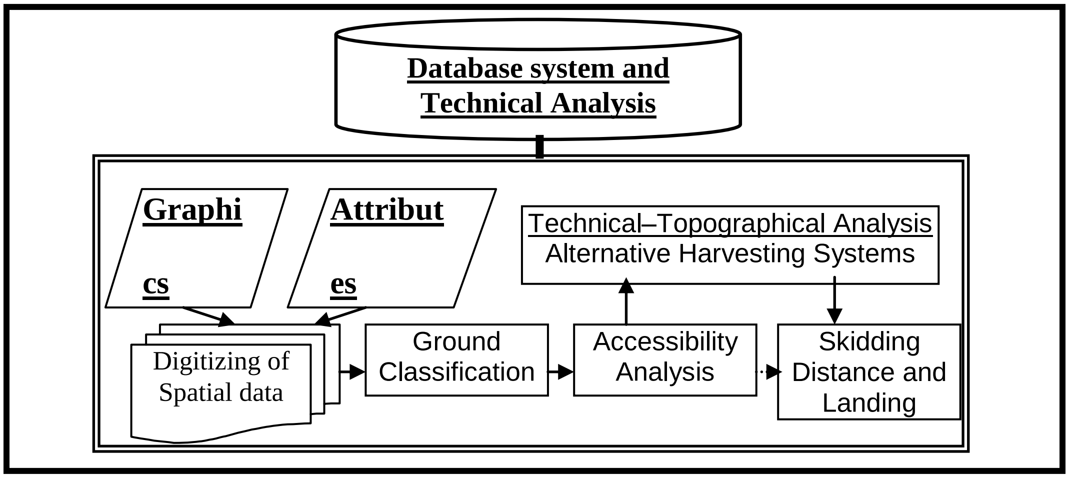

Figure 1. Work flow of database system and technical analysis (Eker, 2004)

2. By using of GIS technology (like ArcGIS), the harvesting compartment ground is functionally classified (Samset, 1979; Acar, 1994) according to slope groups to determine appropriate extraction techniques used in each slope limitation.
3. It is calculated forest road density and opening up proportion. This is accessibility analysis that defines which road opens up each compartment to be harvested.
4. Before starting to technical analysis, alternative harvesting technology can be used in planning district is fixed. Possible cutting, extraction and hauling techniques, which forms harvesting system combination, are selected to topographical conditions, accessibility, and silvicultural intervention of the stands.
5. Transportation boundaries are drawn in each harvesting compartment that is divided to harvesting unit/blocks. The skidding distance and direction is calculated for each alternative extraction technique and point out landing locations via Digital Elevation Model. The real average skidding distance (Erdaş, 1997) for each block is estimated with respect to extraction technique, location of forest road, skidding direction, and length of slope of hill.

2.2. Cost Analysis

The main objective of the AHOP model is to minimize average harvesting unit cost varying of ground features, stand characteristics, assortment types and volume, harvesting method, time, and system. The most appropriate harvesting system for harvest operations is that system has the cheapest fixed and variable/operational cost. Thus, it is obtained a comparison table with respect to economical criterion. This stage of calculation harvesting cost is called as quantitative cost analysis phase (Figure 2).

1. Counting up cutting, felling, bucking, debarking, measuring, skidding, loading, hauling, and unloading cost of per cubic meter of each harvested tree are called harvesting unit cost that is function of standard working time and unit price.

2. Harvesting unit cost for each harvesting system constitutes of cutting and extraction costs. Hauling/transportation cost constitutes of loading, waiting, trip, and unloading cost. Hauling cost is called transportation or physical distribution cost. Both harvesting and transportation cost is calculated with quantitative values to per cubic meter of production.

In this stage, if it requested the most economical harvesting system, road route, and storage can be quantitatively selected. Unfortunately, it is unknown whether or not this harvesting system is acceptable for environmental and societal criterion. For that reason, micro level technology selection procedure (Engür, 1996) is used to compare the harvesting systems for multi-dimensional selection and made use of multi criteria analysis like AHP and Ranking techniques. It is followed the steps mentioned below for this strategy;

1. The influential criteria are to be used to select appropriate harvesting systems and indicators that is sub-criteria are determined by objectives of the state forest enterprise and effective factors on harvesting. These criteria are based on economical, technical-topographical, environmental, ergonomics, and social-institutional goals. To fix the most important criterion, it is used Ranking technique and obtained the weighted value.
2. Afterward, 5 main criteria and 17 sub-criteria that is indicators are evaluated by Analytical Hierarchy Process (AHP) (Saaty, 1989; Engür, 1996; Eker, 2004). In result of the methodology, AHP offers the relative weightiness vector. By reversing of which, it is obtained environmental and institutional impact coefficient including ergonomics and technical impacts. Thus, it is put forward a penalty coefficient appearing although a harvesting system is economically suitable and acceptable but not environmentally is selected.
3. The environmental and institutional impact (penalty) coefficient of the each possible harvesting system is multiplied by quantitative cost of harvesting system, result of which is added to quantitative cost. It is produced environmental and institutional cost (EIC) symbolizing to technical, ergonomics, societal and economical selection criteria. For this methods used in the step, it was inspired from Shemwetta's (1997) methodology (Eker, 2004).
4. Furthermore, seasonal variations in one year can change work productivity, machine usefulness, workforce supply, harvesting cost, and etc. Therefore, 12 criteria such as climate, workforce, market demand, accessibility, etc. are used to examine performance of each season, 4 items in one planning year. There is used a single level comparison matrix in AHP context. According to relative weightiness vector, it is obtained the seasonal impact coefficient. As well, it is added quantitative cost same as mentioned second item and got a seasonal cost (SC) coefficient for each harvesting system (Eker, 2004).
5. On the other hand, harvesting method is influenced to operational productivity and cost, mechanization level, and workforce. In this respect, a cost variation ratio (CVR) is determined to harvesting method that may be short or long assortment in cut-to-length method. The CVR is multiplied by operational cost of harvesting system to define which harvesting method can be appropriate.
6. In the end of the process, quantitative cost that is operational cost of a harvesting system, is collected with EIC, SC, and CVR value. It is newly exposed a qualitative cost of each harvesting system. In the beginning of the strategy, whatever harvesting system that is

appropriate for economical criterion; now, may be inappropriate because EIC, SC, and CVR can qualitatively increase unit cost of harvesting system to be used. Thus, all alternative harvesting systems can be compared with as quantitatively and qualitatively to select acceptable one.

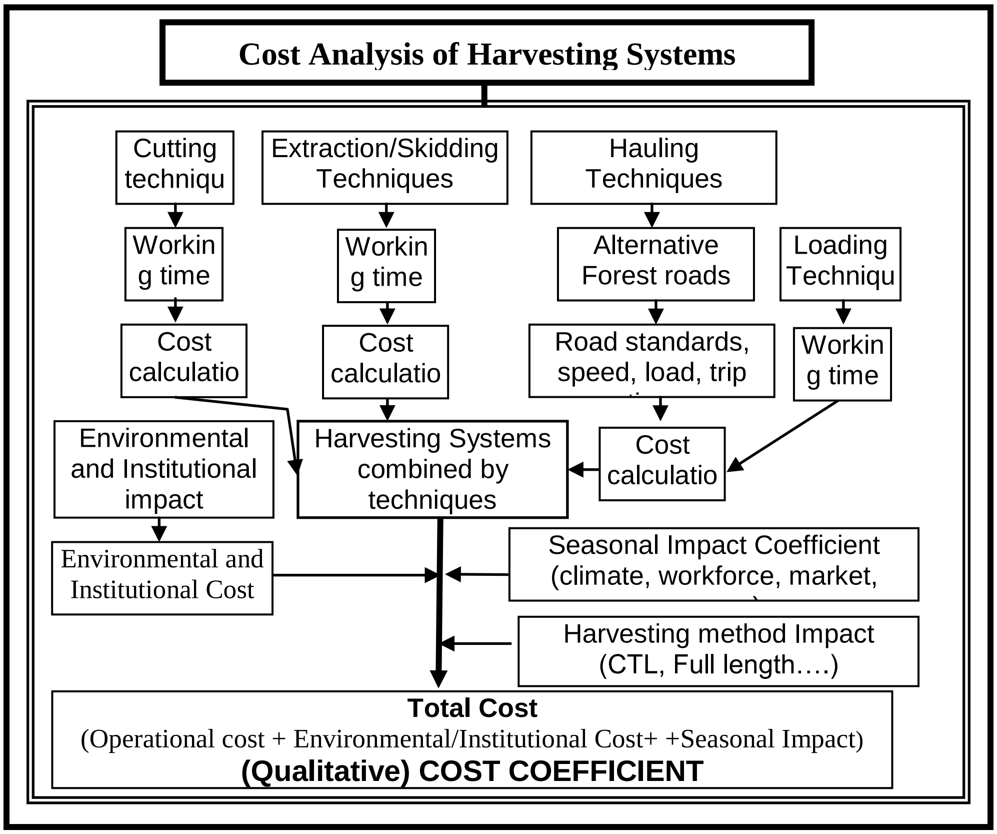

Figure 2. Work flow of harvesting (quantitative and qualitative) cost calculation

2.3. Modeling of the Operational Decisions

In order that operational decisions can be modeled, it is used mathematical modeling method (Dykstra, 1976; Rardin, 2000; Taha, 2000). The objective function of the model is; minimization of operational harvesting unit cost per harvested volume, in annual planning horizon. The cost coefficient is to be used in the model are produced by calculating of cutting, extraction, hauling/transportation costs, which are quantitative harvesting cost of each system. But, in some models, it is used qualitative cost coefficient for multi criteria evaluation to select the best harvesting systems. The modeling process is summarized in Figure 3.

Decision model of AHOP was firstly set up as Linear programming (LP) model (Main Model). Value of the decision variables in the main model were symbolized with continuous, semi-continuous, and integer variables. Afterwards, a hard obligatory constraint, which is that a harvesting block to be harvested in a planning horizon must be harvested in any season, with any harvesting system and method, was added to main LP-based model. This constraint conditioned that a harvesting block or compartment must be opening up at once in a planning year. So, decision variables had to be taken [0/1] binary integer variables. The main LP-based model was subsequently converted to "0/1 Mixed Integer (linear) Programming (MIP)" model. At result, LP and MIP-based two models were developed for AHOP (Eker, 2004).

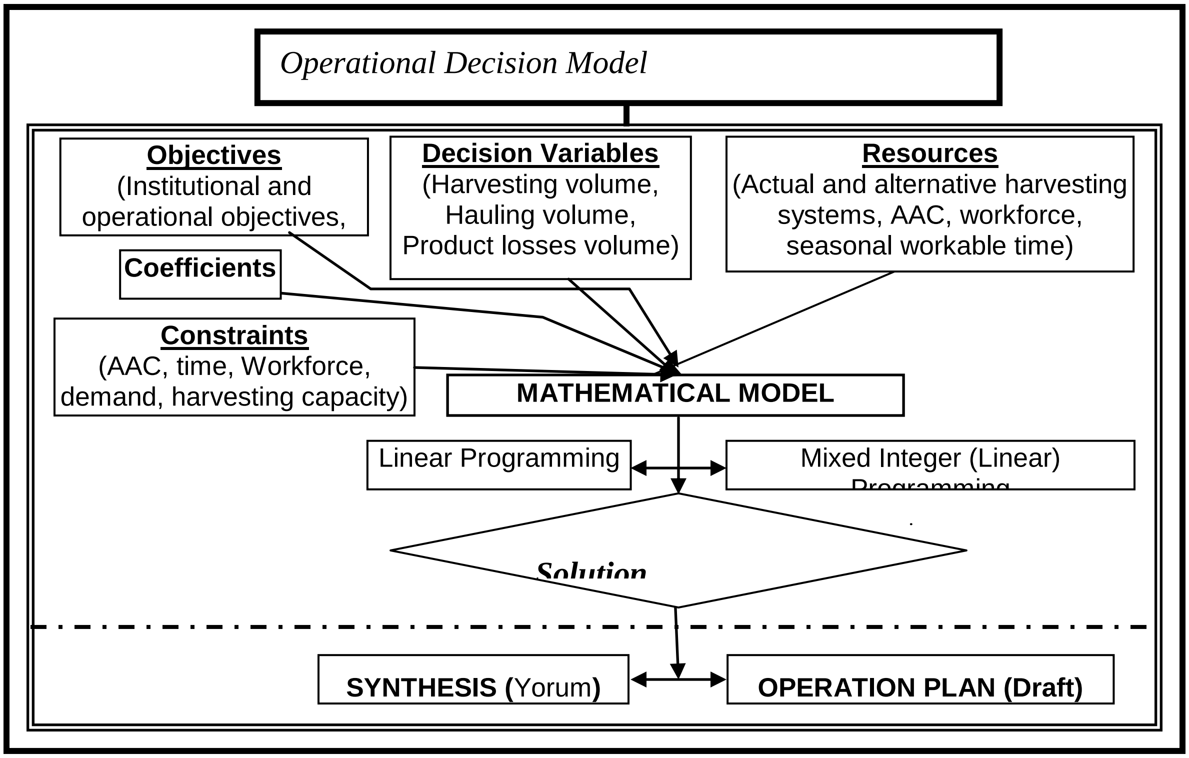

Figure 3. Work flow of mathematical modeling of operational decisions, synthesis, and plan

The mathematical formulation, with index number belonging to a case study given result of which in following section, can be utilizable with integer and semi-continuous variables of AHOP model abstracted from Eker's study (2004) is that;

Objective function;

$$Z_{\min} = \sum \left(PM_p + T_p\right) \qquad \forall p \in P;\ (p = 1, 2, 3, 4) \tag{1}$$

Subject to;

- Harvesting volume to be harvested in one compartment or block is limited by AAC volume allowed by forest management and silvicultural plans.

$$\sum_{p=1}^{4} \sum_{u=1}^{2} \sum_{s=1}^{10} X_{bpus} * ETA_{b\in B} - BETA_{b\in B} = 0 \qquad \forall b \in B;\ (b=1, 2,...,12) \tag{2}$$

- Total harvesting volume to be harvested in a planning horizon, is equal to total volume of harvesting compartment or block, all told.

$$\sum_{b=1}^{12} BETA_b - TOPETA = 0 \qquad \forall b \in B;\ (b=1, 2,...,12) \tag{3}$$

- Each harvesting compartment has to be harvested in one season of the planning horizon.

$$\sum_{p=1}^{4}\sum_{u=1}^{2}\sum_{s=1}^{10} X_{bpus} * ETA_b = 1 \qquad \forall b \in B; \text{ (b=1, 2,...,12)} \tag{4}$$

- Harvesting volume to be harvested in each season is limited by minimum and maximum seasonal limitations.

$$MinHQ_p \le HQ_p \le MaxHQ_p \qquad \forall p \in P; \ (p = 1, 2, 3, 4) \tag{5}$$

- Transported timber volume from each harvesting compartment cannot too much more than harvested volume in that compartment.

$$\sum_{p}^{4}\sum_{u}^{2}\sum_{s}^{10} X_{bpus} * ETA_{b\in B} - \sum_{p}^{4}\sum_{u}^{2}\sum_{r}^{8} Y_{bpur} \ge 0 \tag{6}$$

- Total volume to be transported in each season, should be equal or less than harvesting volume in the same season.

$$\sum_{b}^{12}\sum_{u}^{2}\sum_{r}^{8} Y_{bpur} - TRANSP_P \ge 0 \tag{7}$$

- Transported volume in each season should fit to minimum and maximum limits of the storage, which is function of the market demands.

$$\sum_{u=1}^{2}\sum_{d=1}^{2} DTlpMIN_{pud} \le TRANSP_P \le \sum_{u=1}^{2}\sum_{d=1}^{2} DTlpMAX_{pud} \tag{8}$$

- Harvesting capacity of a harvesting system, depending on productivity, is limited to workable time in one season and number of harvesting system.

1) $$\sum_{b=1}^{12}\sum_{u=1}^{2} VRM_{bpus} * X_{bpus} * ETA_b - S_s P_p = 0$$

2) $$S_s P_p \le Ad_s * PU_p \qquad \forall s \in S; (s = 1, \ldots, 10) \tag{9}$$

- Transported volume in each season depends on number of trucks to be used in transportation and length of workable time in each season.

$$\sum_{b}^{B}\sum_{u}^{U}\sum_{r}^{R} VRM_{bpur} * Y_{bpur} - KMYP_P = 0 \qquad KMYP_p \le Ad_{kmyn} * PU_p \tag{10}$$

- Transportation decision variables have to be positive

$$Y_{bpur} \ge 0 \qquad \forall \ b, p, u, s, r$$

- Harvesting decision variables have to be binary [0/1]. If this constraint is removed from the model, MIP model turn into LP model form.

$$X_{bpus} = \begin{cases} 1 & \text{If harvesting of area } b\text{, is harvested during season } p\text{, by harvesting method } u \text{ system s} \\ 0 & \text{Otherwise} \end{cases}$$

In this model defined sets are;

B is the set of harvesting compartment b, divided into harvesting block/unit
P is the number of time season/period p
U is the set of harvesting method u, symbolizing assortment types
S is the set of all alternative harvesting systems s
R is the set of alternative route r, from each landing to national forest storage
PM p = Total harvesting costs during time season p
T p = Total transportation costs during time season p
Xbpus = Decision variables symbolizing harvesting volume (m3) of compartment b, during time season p, by harvesting method u and system s

Ybpur = *Decision variables transporting/hauling volume (m3) of compartment b, during time season p, by harvesting method u, and route r*
BETAb = *Annual allowable cut of one harvesting compartment b (m3)*
TOPETA = Total AAC in a planning horizon (12 months) (m^3)
HQ_p = Harvesting volume during time season *p* (m^3)
$Min/MaxHQ_p$= Minimum and maximum harvesting volume depending on market demand during season *p* (m^3)
$TRANSP_P$ = Transportation volume to be hauled during season *p* (m^3)
$DTlpMIN/MAX_{pud}$ = Minimum and maximum market demands to be supplied during season *p* , for assortment harvested by harvesting method *u*, in national forest storage *d* (m^3)
S_sP_p = Working time of harvesting system *s* during season *p* (hour)
Ad_s = Total number of utilizable harvesting system *s*
Ad_{kmyn} = Total number of utilizable trucks during season *p*
PU_p = Working time depending on season *p* (hour)
VRM_{bpus} = Operational productivity of the harvesting system *s*, used in compartment *b* during season *p* for harvesting method *u* (hour/m^3)
VRM_{bpur} = Productivity of the route *r* to be used to transport products harvested in compartment *b*, during season *p*, by harvesting method *u* (hour/m^3)
$KMYP_p$ = Working time with trucks during season *p* (hour)

The various packet programs have capacity to solve hard matrix form and special decision support systems can be used to solve this mathematical model. On no circumstances, if a solvable routine is disqualified for integer programming problems in AHOP framework, then it can be used heuristic solution strategy. When it is reached an exact solution, it is checked the model by sensitivity analysis or in different problems. It is tested and synthesized whether or not the operational decision model is appropriate to optimize the main objective function.

The product of the AHOP model is the operational harvest plan. This plan should include information relating to all harvesting operations during a planning horizon, offer operation programs, and conjectural harvesting costs of the systems.

3. CASE STUDY

This AHOP methodology, supporting the operational decision making process through selection of suitable harvesting system in respect of economical, ecological, ergonomic, and social/institutional criteria, was theoretically tested in Turkish Forestry, in Aşağıgökdere State Forest Enterprise located in South of Turkey, as annual harvest operation planning problem. The problem area was amount of 16.352 hectare and the AAC was average 30.000 m^3/year. The number of compartment to be cut in the planning period was 12; 3 of which were to be clearcutting and the others were to be thinned. In the planning area, it was determined that 10 harvesting systems (combination) was to be used in. In this area, all forest operations must be done by forest villagers whose number was 430 people forming a family crew with 4 person. At least, one fourth of the forest villagers must have been worked in the harvest operations. Furthermore, it should be orderly supplied wood raw material of forest industry market in each harvesting season. There was 4 season to be made harvesting. Number of harvesting method was two; short and normal log assortment. The forest product must have been transported the two storage. The harvested products could be transported from different through 2 and 8 routes, changeable for each harvesting compartment, to storage. The problem comprised of 960 harvesting decision variables and 768 transportation decision variables (Eker, 2004).

To solve the test problems, it was used industrial LINDO solver. It could achieve to solve LP model and its extensions by semi-continuous variables, and MIP model by 0/1 binary variables and soft constraints. But, when the hard constraints were added to model, module of LINDO solving MIP model couldn't it. In the case of, it was used optimality tolerance of the solver and developed an optimization-based simple heuristic procedure (Weintraub et all.,1994) in insolvability cases. In each LP and MIP model were modified by using of quantitative and qualitative cost coefficient. Thus, various strategies and scenarios were typically created. But, in this paper, it was not mentioned them.

4. CONCLUSION and RECOMMENDATIONS

AHOP model can offer one-year planning strategy for forest harvesting. The planning arguments of AHOP model are similar to other conventional harvest planning methodology. However, AHOP uses GIS, multi criteria analysis (AHP), and operations research techniques in a unified planning procedure.

It encapsulates three module and each one supports decisions on which harvesting systems are suitable for harvest operations to optimize multi-dimensional objectives. In the first module, it is technically and topographically determined the best utilizable harvesting systems. In the second, it is qualitatively defined which harvesting systems, methods, and season are the best for harvesting in the planning areas. At last module, it is quantitatively made operational decision subject to all constraints. By selecting of the most appropriate harvesting system, season and method, AHOP can enable minimizing of environmental impacts as ecological; reducing of heavy workload, improving of worker health and safety as ergonomics; satisfying of enterprises willing as institutionally; supplying of market demands and satisfying of forest villagers' expectation as socially and politically.

The mathematical model, based on linear and mixed integer programming, was solved subject to structural constraints of the planning problem, it could be determined the most appropriate harvesting systems-season-method and harvesting costs per cubic meter could be minimized at least 4 % to %30 proportion. Both LP and MIP models could work and put forward the optimized results. But, LP as needed its characteristic, presented fractional solution set, which was not applicable for forest compartment because a part of the compartment was to be harvested in one season, the other part was in any season. LP divided into harvesting seasons, and systems. On the other hand, MIP offered exact solution sets. It permitted to be harvest of a compartment during one season time by one harvesting system and method. Therefore, although LP model could minimize objective function as 11 percent more than MIP models, MIP model was found as applicable for AHOP methodology.

On the contrary to traditional harvesting decision making process irrespective of any planning concept, this AHOP methodology offered the best solution to planners and manager with respect to the most economic and environmental, ergonomic, and societal decisions about harvest operation planning problem.

This planning methodology based on the balancing of annual budget and optimizing of objective function in one year time horizon. If it requested, it is can be enlarged modeling framework to two or five year time horizon or narrowed to one monthly time horizon. In addition, AHOP model should be designed as a computer program routine such as a decision support system. Qualitative cost of each harvesting system may not be true way to calculate harvesting unit cost, but it can be effectively used in comparison with systems to select the most suitable one.

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Using an object-based imagery processing scheme to increase the accuracy of delineating Operational Site Units (OSUs) in timber harvest areas from IKONOS image and DEM data integration*

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Abstract
By using new high-resolution satellite imagery (IKONOS, QuickBird) it is possible to detect forestland use structure and to assess environmental change more easily than with conventional lower resolution satellite data. However, due to the high spatial resolution, automatic classification of such imagery based only upon the spectral characteristics (tone, color) of the features can become difficult, especially, in spectrally homogeneous areas. Object-based imagery processing techniques overcome this problem by incorporating both spectral and spatial characteristics of objectives. In this research, an object-oriented eCognition's classification scheme (eCognition is designed to segment the image into units of similar spectral and spatial patterns and to classify those segments according to a pre-defined rule base) was developed which used a DTM with IKONOS imagery (one-meter panchromatic sharpened multispectral data) for the initial segmentation and subsequent object classification. In the multi-resolution segmentation process, the influence of the DTM and multi-spectral bands on object generation was controlled by layer weight, scale parameters, the amount of color and shape factors. The accuracy of the results using this approach is promising compared to pixel-based classification. Results indicate that object-oriented approaches have great potential for improved site-specific operational planning and monitoring system in decision-making processes for timber harvesting strategy.

1. INTRODUCTION

A forest landscape is a spatial mosaic of arbitrary boundaries containing distinct areas that functionally interact (Turner, 1989). Spatial or landscape structure refers to the relative spatial arrangement of patches and interconnections among them (Baskent & Keles, 2005). Remote sensing is more cost-effective technique than field survey to conduct long-term and broad area census. The commercial IKONOS satellite (Space Imaging, USA), one of several new satellites collecting high spatial resolution data, was launched in September 1999 and provides, on request, effectively global coverage of 1 m panchromatic data and four bands of 4 m multi-spectral data in the blue, green, red and near infra-red portions of the spectrum, respectively (Read *et al.*, 2003; Turner *et al.*, 2003). High spatial resolution data with fewer spectral

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 375-381.*

bands in aerial photography and new high spatial satellite images (IKONOS, Quick Bird) can create classification problems due to greater spectral variation within a class and a greater degree of shadow (Laliberte *et al.*, 2004). On the other hand, it contains much information in the relationship between adjacent pixels, including texture and shape information, which allows for identification of individual objects as opposed to single pixels. Image segments are a way of summarizing information from a contiguous cluster of homogeneous pixels. Each image segment then becomes a unit of analysis for which a number of attributes can be measured. These attributes can include dozens of measures of spectral response, texture, shape, and location (Benz *et al.*, 2004; Thomas *et al.*, 2003). Ecologically speaking, it is more appropriate to analyze objects as opposed to pixels because landscapes consist of patches that can be detected in the imagery with object-based analysis (Laliberte *et al.*, 2004). The very important function of GIS is the ability to answer geographical questions based on the information in digital maps with associated attribute database (Baskent & Keles, 2005). Because of the stretch of precipitous mountain forests in Japan, the analysis that combined the topography with other various forest attributes is indispensable for forest operational planning.

The aim of this study is to explore the viability of the object-oriented image analysis for the formation of treatment units in order to appropriate forest operation using the high spatial resolution satellite image (IKONOS) and the digital elevation model (DEM).

2. MATERIALS AND METHODS

2.1 Study site

The study area consists mostly of artificial forests in Miyagawa of Mie prefecture, is located in Central Japan (Figure 1, 34º19'N, 136º15'E) and covers about 1600 ha. Elevations range is between 200 and 1000 m, and topography is precipitous (slope gradient about 10-70º). The forest is an artificial forest characterized by coniferous tree species (cedar and cypress).

2.2 Data source

We used IKONOS satellite (Figure 2, Space Imaging™ processing level: standard geometrically projected) multi-spectral (4 m / pixel) data for about 1600 ha study area. The data were acquired on 23 November 2004. In this study the red, blue and green bands were used for a false-color composite image, which was an available image format (Erdas Imagine image) in the eCognition. Near infra-red and red bands were used to calculate a normalized difference vegetation index (NDVI). NDVI is expressed as

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}}$$

where NIR is the reflectance measured in the near infra-red band and red is the reflectance in the red band (Ustin, 2004). Calculated NDVI was also image format (Erdas Imagine image).

DEM was delivered from Geographical Survey Institute in Japan. Spatial resolution was 50 m / grid. DEM was interpolated by the bilinear interpolation method to 4 m / grid in order to coordinate with the IKONOS data. The slope and the aspect were calculated by using GIS (Arc View 3.2a / ESRI, USA). Calculated topography data was 4 m / grid, which was an available grid format (ESRI ASCII GRID) in the eCognition. The output unit of the slope was a degree. The aspect assigned eight aspects to 1-5 after having output a unit with a degree, which was location from the north. The flat assigned 0.

2.3 Analysis procedure

We used eCognition software (Definiens, 2000) to produce the image segments. The eCognition creates segments based on three criteria: scale, color (values which the grid has) and shape (smoothness and compactness), where color and shape parameters can be weighted from 0 to 1. Within the shape setting, smoothness and compactness can also be weighted from 0 to 1. These criteria can be combined in numerous ways to obtain varying output results. Scale is the most important parameter and affects the relative size of output segmented areas, although there is not a direct relation between the input scale and the number of pixels per the segmented area (Definiens, 2000).

Table 1 shows segmentation parameters used in this study. The study area was segmented by two steps. After it segmented by level 1, they integrated by level 2. The segmentation used in eCognition is a bottom-up region merging technique. In subsequent steps, smaller image objects are merged into larger ones based on the set scale, color, and shape parameters, which define the growth in heterogeneity between adjacent image objects. This process stops when the smallest growth exceeds the threshold defined by the scale parameter. A larger-scale parameter results in larger image objects (Benz *et al.*, 2004).

Table 1 Segmentation parameters used for the analysis

Segmentation Level	Scale	Color	Shape	Shape setting	
				Smoothness	Compactness
Level 1	10	0.8	0.2	0.5	0.5
Level 2	50	0.8	0.2	0.5	0.5

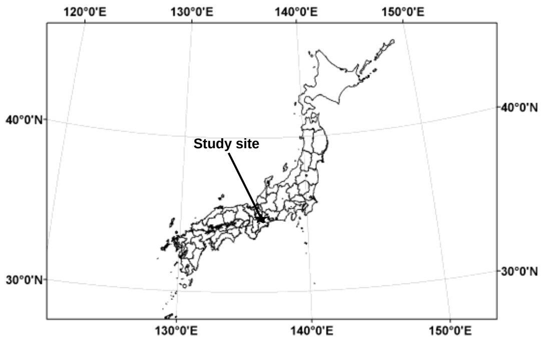

Figure 1. Location of the study site: Miyagawa of Mie prefecture

Figure 2. IKONOS data of the study area

3. RESULTS

The land cover of the study area was segmented by using a false-color composite and NDVI images at a lower level (Figure 3) and at a higher level (Figure 4) based on the image object hierarchy. The number of the objects that was obtained was 11898 (the mean area was 1289.73 m^2) in the lower level. In the higher level, it was merged to 732 (the mean area was 20963.45 m^2, Table2). Topographic characteristics of the study area were segmented by using topography data at a lower level (Figure 5) and at a higher level (Figure 6) as well as above IKONOS image data. The number of the objects that was obtained was 6120 (the mean area was 2537.98 m^2) in the lower level. In the higher level, it was merged to 383 (the mean area was 40554.61 m^2, Table2).

For the formation of treatment units in order to appropriate forest operation, the study area was segmented by using a false-color composite image, NDVI image and topography data (slope and aspect). It was recognized that level 2 suited the segmenting of this area by above-mentioned analysis. Therefore, after the study area was segmented at a lower level, it was segmented at a higher level (Figure 7) based on the object hierarchy. The number of the objects that was obtained was 585 (the mean area was 26030.41 m^2) in the higher level.

Table 2 Unit area by using each levels and attributes

Segmentation Level		Attribute used for segmentation		
		R, G, B, NDVI	Slope, Aspect	All
Level 1	No. of Segmentation	11898	6120	-
	Mean Area (m2) ± S.D.	1289.73 ± 1501.47	2537.98 ±1599.68	-
Level 2	No. of Segmentation	732	383	585
	Mean Area (m2) ± S.D.	20963.45 ± 20833.32	40554.61 ± 25896.17	26030.41 ± 23442.12

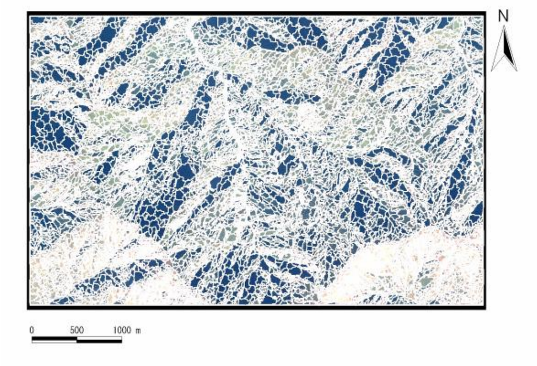

Figure 3. Segmentation of study area by level 1 using a false-color composite image, a NDVI image

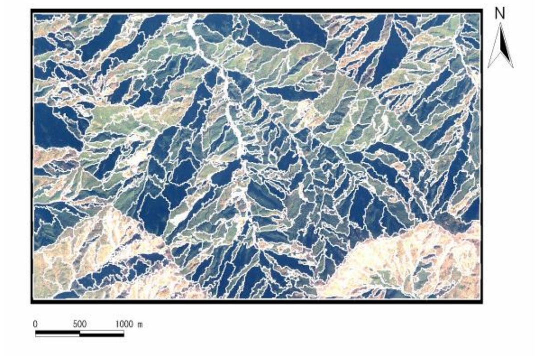

Figure 4. Segmentation of study area by level 2 using a false-color composite image, a NDVI image

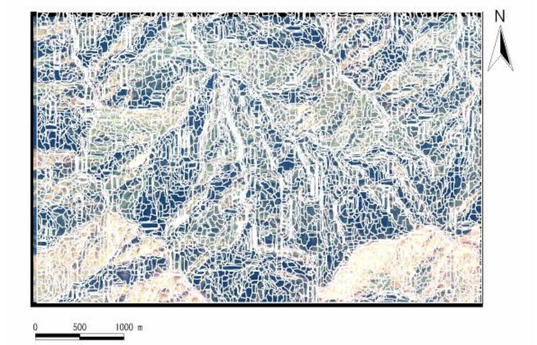

Figure 5. Segmentation of study area by level 1 using geography data

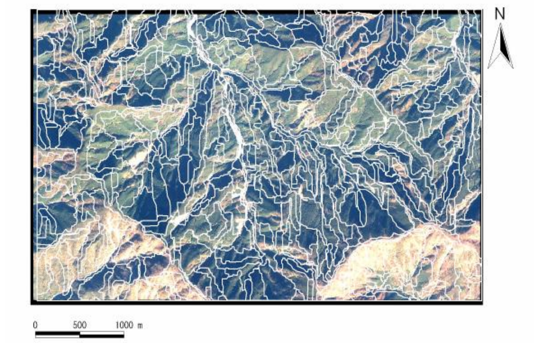

Figure 6. Segmentation of study area by level 2 using geography data

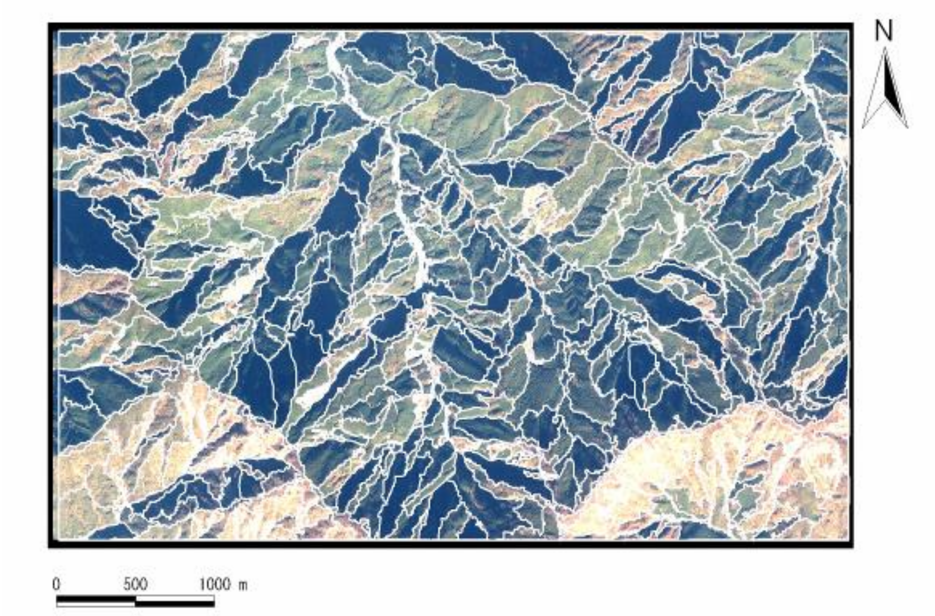

Figure 7. Segmentation of study area by level 2 using a false-color composite image, a NDVI image and geography data

4. DISCUSSION

The importance of concepts in sustainable and nature-oriented forest management has become increasingly recognized in recent years. In addition to governmental institutions, non-governmental organizations such as the Forest Stewardship Council (Forest Stewardship Council, 1994) have developed new, nature-oriented forest management and certification standards (Mrosek, 2001). Therefore, we should depart from the traditional management method by units of stands, owners or regional level.

The use of object-oriented image analysis was proved to be advantageous in this study. Treatment units to appropriate forest operation were generated smaller area compared to that of the stand base planning. The segmented result was the aggregation of pixels sharing similar characteristics in terms of land cover and topography (Figure 7). Forest management planning strives after a desirable course of action for the management of a forest estate (Holmgren *et al.*, 1997). Forest management practices imposed at one spatial scale may affect the patterns and processes of ecosystems at other scales (Tang & Gustafson, 1997). By using the method of this study, operation units which reflect the current condition of the forest was segmented and the management which is based on these units can be practiced. The accuracy of the results using this approach is promising compared to pixel-based classification. Results indicate that object-oriented approaches have great potential for improved forest management information and monitoring system in decision-making processes for precision forestry purposes.

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Mobile Data Acquisition Systems for Documenting Motor-Manual Silvicultural Operations*

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Abstract
Herbaceous weed control and planting of southern pines share a common attribute in that they are both implemented using primarily hand labor in the southern US. Contractors providing these services have had problems documenting the amount and quality of work performed by individual laborers, and in providing auditable data to landowners of the extent of services provided. Electronic systems were developed to resolve these problems. The 'SmartPak' system recorded location while a worker sprayed herbicide and the 'SmartDibble' documented location when a tree was planted. Both systems provided information useful to contractors for operational management and documentation, and data on which land management decisions could be based.

1. INTRODUCTION

Temporary seasonal workers are commonly used in forest management in the US South, primarily in two specific tasks: regeneration planting, and herbaceous weed control. There are many reasons for this reliance on human labor, but the primary driver has been that costs tend to be lower. Mechanical alternatives are not available that provide as consistently good results across the broad range of conditions found in the region.

There are questions, however, surrounding the employment of this temporary labor force, and the work they produce, that have caused some controversy. Large landowners, and the silvicultural contractors they employ, are seeking ways of improving the quality and accountability of work produced using seasonal laborers. This report will outline the authors' efforts to create information systems for documenting the output of manual labor in herbaceous weed control and hand planting.

2. BACKPACK HERBACEOUS WEED CONTROL

Woodland Specialists, a silvicultural services contractor located in Chapman, AL, developed, in association with Auburn University Biosystems Engineering Department, a backpack spray system to reduce concerns with employee safety and quality assurance for clients. Design changes resulted in a new type of spray rig that addressed health concerns and added monitoring electronics to record spray system performance. Their objectives in creating the new system were:

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 383-392.*

1. Create a safer, healthier work place for their employees to reduce turnover and increase awareness of job performance standards, and

2. Develop a data collection system to document worker activity and chemical spray coverage over an entire tract.

The system they produced has been dubbed the 'SmartPak' and has been deployed in the field for one full season.

Worker safety concerns arose because of the nature of the work being performed. Herbicides are used extensively in forest stand management in the US, especially in the South, where an estimated 93 percent of silvicultural herbicides are sold annually (Shepard and others 2004). Their use in silvicultural stand management can be broken down into three primary objectives: site preparation, herbaceous control, and release (woody competition control). Site preparation and release treatments are typically broadcast applied using mechanized aerial or ground-based systems. Herbaceous weed control is usually applied a short time after planting to provide a window of time within which the seedlings can become established without competition. Applications are usually sprayed in bands directly over the seedlings, saving chemical and providing equal benefit to broadcast application. Dubois and others (2003) reported estimates of silvicultural chemical usage from the four largest herbicide distributors in the South. Their data indicated about 950,000 ha of pine plantation were treated with some form of herbicide in 2002, with nearly 25 percent representing herbaceous competition control.

The application of herbaceous competition control at stand establishment seems to be currently in favor, and one common means of implementing this type of prescription is through banded spray using backpacks. Miller (1998) reported that, during the mid 1990's, only about one percent of herbicides used in the South for silvicultural purposes were applied using backpacks. That figure has certainly increased over the ensuing years. Dubois and others (2003) found in their survey that backpack application was used on about 16 percent of total pine plantation acres treated in 2002. The increase can be attributed to reduced chemical use compared to broadcast applications, lowering costs, plus a decrease in acreage mechanically site prepared, reducing the area on which spray machinery can subsequently operate cost effectively.

Chemical application by hand can be a risky business, for both the person carrying the backpack and that person's employer. For the worker, the risks are primarily associated with inadvertent contact with the chemicals being applied. In the past, backpack applicators consisted of a tank and a wand with which the worker sprayed the chemical. Spray pressure was typically maintained using a hand-powered pump, a significant physical burden. From a safety standpoint, this system forced the operator to walk through vegetation that had just been sprayed.

Shepard and others (2004) reported that 90 percent of herbaceous weed control chemicals used in the South were classified as imazapyr, metsulfuron methyl, or hexazinone, which are relatively nontoxic (LD_{50} about 10 to 30 times that of caffeine, Campbell and Long 1995). Significant exposure of workers is possible, however, because of the nature of the typical backpack sprayer and how it is used. Long-term exposure effects are not known, and neither is the effect of inert ingredients used in commercial forms of the herbicides. Most herbicide manufacturers do not reveal exactly what additives their products contain, but enough is known to further discourage exposure of workers.

Besides having to control exposure of workers to herbicides, application contractors must provide their clients with evidence of the quality of the services rendered. Ideally, a contractor should be able to provide an auditable record of the amount of chemical applied at what locations. These data are useful for billing clients and in resolving disputes over efficacy of the treatment.

2.1 Modified Spray System Design

Spray system changes implemented by Woodland Specialists included mounting the tank on an ergonomic backpack frame to increase worker comfort, and conversion of the hand-powered spray system to use an electric pump, reducing physical demands placed on the worker. Spray nozzles were mounted in a fixed, rearward-facing direction so the worker was not constantly moving through chemically treated vegetation. These modifications reduced the level of exertion required while spraying and freed the worker's hands to help maintain balance when moving through thick vegetation and slash. A photo showing the SmartPak system in use is found in figure 1.

A spray monitoring system was used to record the state of the spray pump and location of the worker over time (a photo of which is also shown in figure 1). A microcontroller sensed the pump being switched on and began recording position output from a global positioning system (GPS) attached through a serial port. Data were recorded at 1-s intervals on a compact flash card. Garmin model 18 and 16 GPS units have been used, and both have proved successful.

Included in the monitoring system was an LCD screen through which the microcontroller could provide information to the operator. Output included updates on the state of switches and the GPS (satellite and WAAS availability), plus an error field that reported problems with data storage and other high-level system functions. The microcontroller also kept track of travel speed of the worker and gave constant updates via the LCD screen. The operator would typically be given a target speed at which to walk in order to apply the herbicide at the prescribed rate.

Figure 1. Workers using SmartPaks to apply herbicide for banded herbaceous weed control. On the right is a photo of the SmartPak electronics, including the microcontroller housing, LCD screen, and GPS.

2.2 Field Experience Using the System

Woodland Specialists employed the SmartPak system in herbaceous competition control contracts on over 6000 acres during the 2005 spray season. About 20 total units were in use over that period, most on backpack units, but a few were used on mechanized spray equipment to track their application coverage. In general, the systems were deemed a success and plans are to use them again in the coming spray season.

Worker satisfaction with the SmartPaks was generally good, with the exception of a perception that, perhaps, productivity was not as high as desired. Wages were calculated on a linear distance application basis, so workers were very sensitive to any changes that affected their ability to cover ground. Although some spray system modifications enhanced productivity (the electric pump, hands-free operation), spray tank size had to be reduced in order to accommodate batteries, pumps, and other components. Most hand-powered spray units have a 19-liter tank. That volume was reduced by about 20 percent on the SmartPak, requiring additional trips to refill. The electronic components added 850 grams to the SmartPak, the battery about 3.5 kg more, but wet weight of the units (hand-powered and SmartPak) was roughly equivalent.

Operation of the SmartPaks required the workers to pay close attention to the feedback provided by the microcontroller, especially regarding battery status and walking speed. There was some concern on the part of field technicians that the feedback given workers on speed did not have enough resolution. The speed data were extracted from the GPS information and were only available to the nearest $1/10^{th}$ mph. The technicians, and presumably workers, felt this level of accuracy might not have been sufficient to ensure uniform spray coverage.

As one might expect, the SmartPak units deployed in the 2005 season proved not quite as durable as hand-powered units. Field technicians working with the spray crews felt the 2005 units would work reliably for about 3 to 4 months in the field. Spray season might last 6 months in that region of the country. Some of the failures observed had to do with the backpack carrier systems, which were essentially hiking pack frames that could not sustain the abuse suffered in field work over long periods of time. Units used later in the season were strengthened. Vibration and impacts during transport to and from the field were thought to decrease reliability of some of the electronics, but contamination from water or dirt was not a problem. Some of the components to be used in units for the coming spray season will be modified to increase the service life of the systems.

Workers were required to charge enough batteries every evening for the next day's work. The packs required at least two batteries per day in normal operation. Workers were not always happy with the responsibility of dealing with batteries, but seemed to accept it.

In the field, the SmartPaks worked about as well as could be expected for a prototype system. One area of operation that proved to be somewhat burdensome, however, was handling the constant stream of data being generated. This task required an estimated 30 to 40 hours per week for each of two technicians supervising seven spray crews. Over the course of the season, about 6 gigabytes of information were downloaded from the spray units, summarized, and transferred into a geographic information system (GIS). There was consensus among technicians that this process could be improved greatly.

2.3 SmartPak Conclusions

After one season of extensive field testing, the management of Woodland Specialists felt the enhanced spray systems were worth the extra effort required to keep them operating. They cited the auditable documentation of work performed as the single greatest benefit of the systems. The data derived from the Smartpaks were used in settling accounts with landowners concerning number of acres treated and in resolving disputes over spray efficacy. Being able to show exactly where chemical had been applied proved a significant business advantage for the company. A map, such as that in figure 2, established a basis from which disputes could be resolved. The maps also provided a means of distinguishing Woodland Specialists from their competition and contributed to an atmosphere of trust with clients. When disputes arose over the level of herbaceous control in a particular tract, the company was able to show that they had in fact applied the chemical at the prescribed rate and that the prescription, or the chemical itself, must have failed.

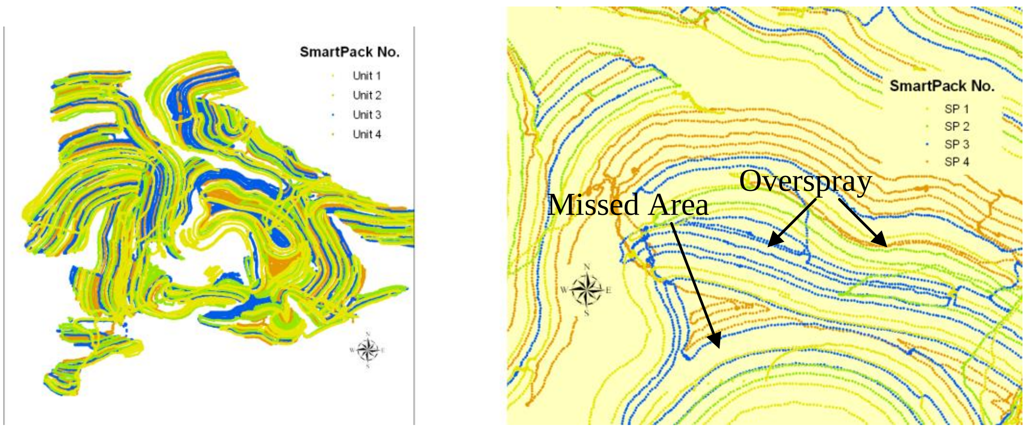

Figure 2. The as-applied map on the left shows herbicide coverage for a tract by 4 workers using the SmartPak. On the right is a detail of the map showing areas of over- and under-spray.

Although other expected benefits, such as reduced chemical use through accurate application, were not as readily apparent, the SmartPak proved to be a useful tool in managing and educating workers. Maps of over sprayed and missed areas gave field technicians an unequivocal means of expressing concerns about poor performance to workers that most often did not speak English. Figure 2 also includes a detailed depiction of an area from the map on the left. Areas of over- and under-spray, as well as the identity of the person responsible for the errors, are easily seen.

3. HAND PLANTING

Every year, US law allows issuance of 66,000 H2B guest worker visas to help companies involved in businesses other than agriculture hire workers they cannot recruit locally. In recent years, the majority (over 20 percent) of the visas issued have been for forest management activities (McDaniel and Casanova 2005). Regeneration planting of southern pines has been the largest single use to which H2B visas have been applied. McDaniel and Casanova (2005) reported that only about 8 percent of tree-planters working in the southern US were citizens, and about 84 percent were working with H2B visas. The remainder was on other types of visas, or undocumented.

A series of reports in the Sacramento Bee newspaper published in 2005 alleged serious mistreatment of workers hired for forestry work under H2B visas (Knudson and Amezua 2005). The articles reported many types of abuses, most involving taking advantage of the workers' dependency on the employer to maintain their status in the country. This publicity has focused a great deal of attention on the tree planting industry in the US. Some of the most critical has involved payment of planters. It has been alleged that workers were defrauded by unscrupulous employers that manipulated production figures, and the Southern Poverty Law Center of Montgomery, AL has filed a legal complaint on behalf of guest workers against the three largest contract planters in the country seeking redress (Linn 2005).

These legal troubles have created a tense atmosphere among companies involved in regeneration services. As in the case of herbaceous weed control, those companies that do their best to treat workers fairly and in compliance with laws feel they should be rewarded for the extra costs that effort entails. Unless they can fully document that compliance, however, their claims of unfair competition from other, less scrupulous, employers have no basis.

Woodland Specialists has, again working with Auburn University Biosystems Engineering, begun to investigate the use of electronic monitoring systems to document worker activity, this time involving tree planting. The concept, as in herbaceous weed control, was to create the technology to map all activity carried out by workers on a site, For planting, this meant showing placement of all trees across an entire stand. Such technology would form the basis of a fair piece-rate pay incentive program for workers, create an auditable record of work done for a landowner, and be a tool available to implement the concepts of 'precision forestry'. Given data on every tree in a stand, including its location, managers can focus attention and resources to the level of the individual tree, rather than the population. Managing for average conditions on a site will produce average results over time, but, as the technology becomes available, optimizing the growth potential of every individual should maximize the output of the entire stand.

The objectives of the work have been to

1. Create a wearable device that accurately records the location and time of a tree-planting event, and to
2. Use that device to map tree locations in hand planting operations.

A prototype version of such a device, the 'SmartDibble', was subjected to limited tests in the 2005-2006 planting season.

3.1 The SmartDibble

Trees are hand planted using one of two implements, a dibble or hoedad. Both are designed to create a hole in which the seedling is placed, the difference is in the motion required by the worker to use them. The hoedad uses an over-the-head swinging motion, much like an axe, while the dibble is an impact-type device, punched in a downward motion into the ground. While hoedads are used quite extensively in the southern US, dibbles are recognized as being superior from a quality of planting standpoint and were the focus of this research.

The tree planting event 'sensor' developed for the project took advantage of the fact that every tree required a rather abrupt motion on the part of the worker to create a hole in the ground. An accelerometer was used to detect impacts of the dibble with the ground, and a microcontroller, when an impact was observed, recorded the event along with a time stamp and a position from a GPS.

The proof-of-concept system built used a modified SmartPak data collection system to monitor planting activity, seen in figure 3 below. The dibble was outfitted with a short section of steel pipe, welded perpendicularly to the shaft, housing an accelerometer, a voltage comparator, and a wireless communication system. When acceleration exceeded a threshold value, an ‘event’ notice was radioed to the SmartDibble controller, which was carried by the planter. Upon receiving notice of the planting event, position was read from a Garmin model 18 GPS, interfaced through a serial connection, and the information stored on a compact flash card. The SmartDibble interface also included an LCD screen that reported number of events observed, information on GPS status, and battery condition.

Figure 3. The SmartDibble, a tool to collect information on tree location while planting, is being carried in the right hand of the gentleman on the right in the photo. The accelerometer electronics are housed in the small pipe attached to the dibble shaft. Impact events are radioed to a modified SmartPak unit carried in a pack on the operator’s back. The system monitors position information output from a GPS attached to the operator’s right shoulder.

Unfortunately, the prototype SmartDibble system was not ready for deployment until near the end of the planting season and received only limited testing. Preliminary tests of the system were conducted under field conditions using professional planting crews. Modifications were made to suit the operators, mainly re-positioning of the acceleration sensor housing on the dibble itself. After modifications, the system was more thoroughly tested for a single day of planting – the last day of the season for the crew doing the work.

Planting tests were made using a single member of a cooperating crew of about 12 workers. This particular crew normally used hoedads for planting and had only limited experience using dibbles. The operator using the SmartDibble system, in fact, had never used a dibble before. The first part of the test, therefore, involved training the worker in how to plant using a dibble. Once the training was completed, the worker began planting on a portion of the site away from the remainder of the crew. The site had been bedded and trees were planted at a 2-by-5 m spacing. The worker adapted quickly to the dibble and wound up planting 619 trees using it.

Planting a tree with a dibble, or hoedad for that matter, involves at least two impacts of the instrument with the ground: one to open a planting hole, and one to close it. In actual practice, the number can be much higher, depending on soil conditions, or the presence of rocks or roots. Testing of the dibble, therefore, was intended to answer three main questions. First, was it practical to use? Second, could a single planting event be detected from a sequence of multiple dibble impacts? Third, was the position associated with each planted tree accurate enough to add value to future management activities? Practicality was assessed qualitatively – the operator was simply asked for his feedback about using the system. Accuracy of the tree location was measured by associating a 'true' tree position with each dibble impact. The true position was established using a Trimble GeoXT GPS using post-processed correction. Finally, the question of multiple impacts was investigated by direct observation of the SmartDibble while being used. For a subset of planted trees (171), the data collection system was removed from the operator and carried by another person. That person could observe, and record, when the system detected an impact event by watching the event counter increment. In this manner, an impact event could be directly correlated to a true tree position.

Figure 4 is a map showing all impact event positions recorded by the SmartDibble, as well as actual tree locations as established using the Trimble GPS. It was evident from the map that positional accuracy of the SmartDibble system was quite variable over time and errors were of a relatively high magnitude in general.

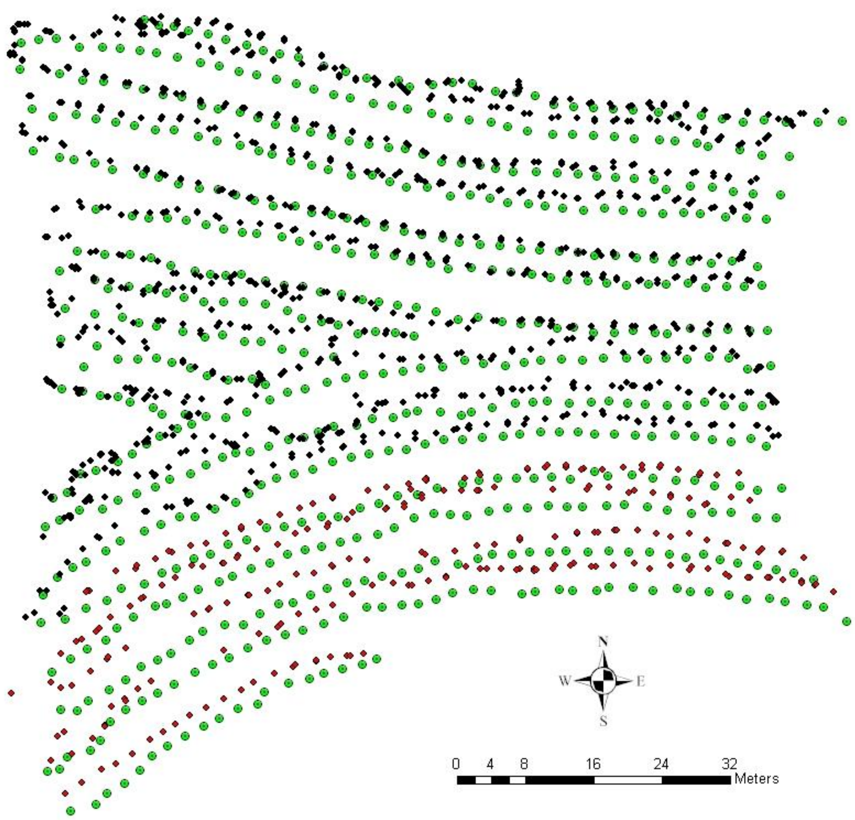

Figure 4. Map of planting locations established using two positioning systems: the SmartDibble, and a Trimble GeoXT GPS system. Green dots are the 'true' positions from the Trimble. The black and red markers are those positions from the SmartDibble. The black markers indicate those taken without independent evidence of the microcontroller recording an impact. The red markers indicate those positions for which the impact information was also recorded by a human observer.

For the 171 trees for which detailed knowledge of impact event timing were available, it was found that, for the conditions tested, the characteristic two-impact scenario for each planting event (one each for opening and closing the hole) only occurred about 1/3 of the time (36 percent). In slightly over half the cases (53 percent), only one impact was detected for each tree. No impacts were detected for 11 percent of trees. This result was likely due to the relative ease with which the dibble could be inserted into the ground. The bedding of the site made planting very easy, and the operator, to conserve his energy for the day, did not exert more force on the dibble than necessary to plant the tree. The comparator used to monitor accelerometer magnitude was probably set at too high a threshold, and these soft impacts were missed. Data in figure 4 tended to support this since those trees for which no impact was detected tended to be clustered in small areas, even between rows. This was likely due to locally high moisture content, organic matter content, or soil textural differences.

Those same 171 tree positions were sorted by hand and assigned to a true tree location. The assignment was made using notes taken in the field on what dibble event number was associated with what tree, and, when there was some doubt, based on time of the event relative to other events. In some cases, the assignment based on this information was overridden because it just did not 'look' right. In those cases, a discretionary choice was made regarding to which tree the event was assigned. The average deviation of the SmartDibble and true positions was about 2.3 m for the 171 trees in the sample. This level of accuracy was considered insufficient by the landowner to implement tracking of genetically improved seedlings, an application being considered at this time. Some of the accuracy was undoubtedly a bias introduced because of how the system was carried and used. The operator was working on bedded ground and, because he was right-handed, tended to walk along the left side of the beds in order to avoid soft footing. The GPS antenna was also mounted on the left shoulder of the operator. Both of these practices tended to impose an offset to the measured positions.

Practically, the SmartDibble seemed to work fairly well. The workers that used it did not complain about the monitoring system, but complained quite strongly about the dibble itself. They were accustomed to a particular style and size and were reluctant to depart from that in any way. Perhaps their dissatisfaction with the dibble masked any feelings about carrying the monitoring equipment, but this was hard to judge. We observed no decrease in productivity because of the system, but, again, this was hard to judge accurately. Although no problems were encountered, the most vulnerable part of the system was likely the wireless antenna. Modifications will be made to this before using the system next year.

4. CONCLUSIONS

Manual operations are used widely in forest management in the southern US and likely will be in the future. Many concerns have been raised about the quality of work performed by hand and the systems presented in this report were developed to document the rate and spatial attributes of two forms of manual labor. The SmartPak system documented application of herbicides for herbaceous weed control, providing maps of where and when chemical was sprayed, as well as who performed the work. Although collecting the data was problematic, it has proved its value to contractors in documenting for landowners work performed and in resolving efficacy disputes. Although it has not been applied in practice as of yet, similar benefits should accrue from use of the SmartDibble system.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Using GPS to Document Skidder Motions – A Comparison with Manual Data Collection*

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Abstract
A GPS receiver with external antenna was used to track a Cat 525B rubber-tired grapple skidder. The GPS was set to record line data on a 5 second and 1 second time interval and elemental times were extracted and tested to determine if they were statistically different than elemental times collected manually. Statistical analysis was used to compare travel empty, grapple time, travel loaded, un-grapple time and total cycle time between the two methods of time data collection. It was found that GPS times were not significantly different for travel empty and grapple time, but travel loaded and un-grapple time showed significant differences between the two techniques. GPS was shown to be a useful tool for collecting data on trail work, idle time and searching for logs unsuccessfully. Also, the 5 second time interval proved to be easier and quicker to analyze that the 1 second time interval and was just as accurate. Ideally, GPS in combination with some manual time data collection on the logging deck would give the most reliable and accurate time data for productivity studies on rubber-tired grapple skidders.

1. INTRODUCTION

A continuous time study of a single skidder requires at least 2 people to conduct the study. One person will sit on the log deck with a stopwatch and 2-way radio and record the movements of the skidder on the deck, while the other person will be located in the woods to record the movements of the skidder as it picks up the bundles of logs. The researchers stay in contact with the 2-way radios and notify each other when the skidder leaves the woods to return to the deck and when the skidder leaves the deck to get another bundle. The 2-way radios are necessary for collecting travel empty and travel loaded times. The person on the deck will also record such times as idle time and time spent cleaning the deck.

Global positioning systems (GPS) have created new and simple ways to track the movements of all types of vehicles, yet the logging industry has been slow to incorporate this technology in their operations. Wide area augmentation system (WAAS) is a form of differential correction that enables the GPS receiver to record more precise measurements. This study used GPS along with Pathfinder Office™ software to analyze the difference between the traditional method of collecting time data for a continuous time study of rubber-tired grapple skidders and collecting time data using a GPS for a continuous time study of rubber-tired grapple skidders. The purpose of this study is to determine whether or not one can use GPS accurately for an unattended time study of rubber-tired grapple skidders.

1.1 Review of Literature

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 393-402.*

Time-motion studies are the essential way to collect productivity information on forest machines. Textbooks that include details on how to properly conduct time-motion studies have been written by Miyata et al. (1981), Barnes (1980) and Niebel (1988).

Miyata et al. (1981) analyzed the stopwatch technique for continuous time studies on logging operations and list some distinct disadvantages such as:

1.) Requires highly skilled observers.
2.) Requires tedious recording of data over long hours.
3.) Becomes costly because you need at least as many observers as there are pieces of equipment and often two observers per machine.
4.) Following logging equipment through a stand is hazardous.
5.) Reducing data is difficult and time consuming.
6.) Accuracy of data gets questionable at the end of a long, exhausting day.

Published studies using manual time data collection technique on rubber-tired grapple skidders include: Gardner 1978, Blake 1987, Miller et al. 1987, Moore 1987, Tufts et al. 1988, Robe et al. 1989, Gingras et al. 1991, Kluender and Stokes 1994, Brinker et al. 1996, Lanford and Stokes 1996, Hartsought et al. 1997, Kluender et al. 1997, Hartsought et al. 1998, Klepac and Rummer 2000, and Wang et al. 2004a. These studies all used a stopwatch and 2-way radios to time the skidders as they performed their various tasks.

"Siwork 3" is a new type of time study software created by the Danish Institute of Forest Technology. Productivity studies of skidders using Siwork 3 time study software include Visser and Stampfer (2003), Spinelli and Hartsought (1999), and Wang et al. (2004b). These studies, even though they are using new software to collect time data, still follow the same guidelines of the time-motion studies outlined by Miyata et al. (1981).

Continuous time studies using GPS to record and measure cycle times have been documented by Spruce et al. (1993), McDonald (1999), McDonald et al. (2000), Taylor et al. (2001), Veal et al. (2001), Holden et al. (2001), and McDonald and Fulton (2005).

This study used the methods that were outlined by Miyata et al. (1981) for conducting time studies on forest machines, but with some slight modifications to the way times are taken. Elemental times for all tasks a skidder performs were collected using both the manual time data collection techniques and GPS. The data were analyzed and comparisons were made for each time element in the study.

1.2 Objective

Determine whether a GPS receiver with an external antenna set to record data on a 5 second (or 1 second) time interval could be used to collect data accurately for a continuous time study of a rubber-tired grapple skidder working on a second thinning in a loblolly pine plantation.

2. METHODS

The GPS receiver was set to collect line data on a 5 second and a 1 second time interval. The study was conducted on a second thinning of a loblolly pine (*Pinus taeda*) plantation that was being harvested by Slaughter Logging LLC (Dennis Aucoin, owner) Clinton, Louisiana.

The operation is a typical mechanized logging operation that operates with one Cat 525 B skidder, one Tigercat 750 feller-buncher, and one Tigercat 230B Loader. This thinning crew produces between 6 and 8 truck loads of chipNsaw and pine pulp logs per day. The crew normally conducts first and second thins of pine plantations in southeastern Louisiana.

Figure 1. Picture of a Cat 525B Rubber-Tired Grapple Skidder wit GPS antenna installed on roof (barely visible near front of roof).

A Trimble GeoXT GPS receiver (WAAS enabled) was used with a Trimble Geo3 mini antenna which is 1.5 inches wide by 1.9 inches long by 0.5 inches high. The small size of the antenna prevented it from being knocked off by branches or brush while operating in the stand. The GPS unit was set up in the skidder with the antenna wire running out of the door and connected to the roof of the skidder.

While the GPS was recording the movements of the skidder, one person was stationed on the deck while another person was stationed in the forest stand to manually record the movements. Times recorded in the field were listed in a spreadsheet:

1. Trail Work
2. Travel Empty
3. Grapple Time
4. Travel Loaded
5. Delimb (skidder backs drag into delimbing gate)
6. Un-grapple Time
7. Deck Time
8. Hauling Slash
9. Idle Time
10. Wait on Loader
11. Searching for Logs unsuccessfully
12. Miscellaneous Time

GPS Pathfinder Office™ 3.0 was used to display the GPS data in a map view which could be manipulated. By scrolling through each point, the movements of the skidder were easily recognized and times were recorded from the times shown on the position properties box and recorded in an excel file.

Wait on Loader times were combined with Idle times since with the GPS method one is not able to tell the difference when the skidder is waiting on the loader or idling for other reasons.

Null Hypothesis: A GPS receiver with external antenna set to collect line data on a 5 second (or 1 second) time interval in a rubber-tired grapple skidder is just as accurate as collecting time data manually (Alternative Hypothesis = less accurate).

Reliable statistical analysis could only be performed on complete data, so Travel empty, Grapple time, Travel loaded, and Un-grapple time were the only time elements in which statistical analysis was used to make comparisons. There were a total of 6 half days since each day was broken down into data collected in the morning and data collected in the afternoon. March 24 AM is referred to as HD1, 3/24 pm is HD2, 3/25 am is HD3, 3/25 pm is HD4, 8/10 am is HD5 and 8/10 pm is HD6.

P-values were calculated for the difference between the times collected manually and by GPS for travel empty, grapple time, travel loaded, un-grapple time and total cycle time. The p-value is the probability of committing a type 1 error if the actual sample value of the statistic is used as the rejection value. A p-value is the smallest level of significance for which the null hypothesis would be rejected with that sample. For this study p-values of less than or equal to 0.05 would fall into the rejection region and the null hypothesis would be rejected. P-values of greater than 0.05 would prove no difference between the two methods of collecting time data and would fail to reject the null hypothesis. Type 1 errors occur when a true null hypothesis is rejected.

3. RESULTS

Data Collection

Figure 2 is an example of a line file that was extracted from the GPS that after the skidder finished pulling the bundles to the deck (set, landing). The log deck is easily discernable from the line file created by the GPS unit. The points where the skidder operator pulled off the trail to back up to the bundles are also easily discernable from the triangle shaped lines protruding from the main trail. The skid trails and logging deck are clearly discernable from the line file produced by the GPS receiver.

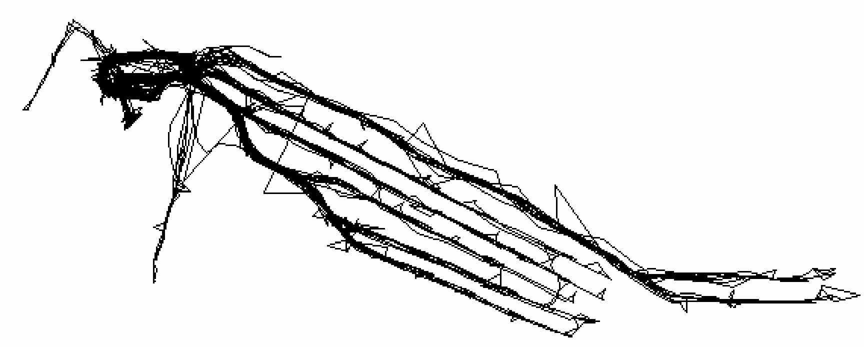

Figure 2. Example of a line file that was collected by the GPS from the skidder activities on one half day (HD) of the study.

Less than 1% of the points were deleted for cause of poor accuracy (high PDOP). The antenna was located about 3 meters above ground level, giving the GPS unit obviously improved reception over identical hand-held units.

Travel Empty, Grapple Time, Travel Loaded, Un-grapple Time

The results of univariate procedure on the major time elements are shown in Table 1. P-values less than 0.05 means the difference between the recorded times from the two methods of data collection is significantly different than zero. If the p-values are greater than 0.05 than the differences between the two methods of time data collection are not significantly different than zero.

Table 1. P-values for the differences between tasks and half days for travel empty, grapple time, travel loaded and un-grapple time.

Univariate Procedure						
			P-Values			
Element	**HD1**	**HD2**	**HD3**	**HD4**	**HD5**	**HD6**
Travel Empty	**0.3779**	**0.7955**	0.0125	**0.1690**	**0.3186**	**0.1972**
Grapple	**0.2239**	**0.8085**	**0.0738**	**0.8827**	**0.7354**	**0.2371**
Travel Loaded	0.0019	0.0238	**0.4890**	**0.1590**	0.0001	0.0046
Un-grapple	0.0330	0.0003	0.0043	0.0023	**0.7568**	0.0027

Looking For Logs Unsuccessfully

Table 6. Total observations, sum of seconds and measures of dispersion for looking for logs conducted on each half day of the study.

Looking for Logs		Total Observations	Total Seconds	Average Seconds	Standard Deviation
HD1	Manual	0	0	0.0	0.0
	GPS	0	0	0.0	0.0
HD2	Manual	0	0	0.0	0.0
	GPS	3	1418	473.0	628.7
HD3	Manual	0	0	0.0	0.0
	GPS	0	0	0.0	0.0
HD4	Manual	0	0	0.0	0.0
	GPS	1	110	110.0	0.0
HD5	Manual	1	85	85.0	0.0
	GPS	2	150	75.0	14.1
HD6	Manual	2	92	46.0	22.6
	GPS	2	124	62.0	21.2

Looking for logs was a part of the study that was included after the first day when we noticed the skidder going down skid trails where there were no bundles. This time element is difficult to isolate with the manual data collection method of collecting time data since it is often missed because one cannot see the skidder when this happens.

<u>Total Cycles</u>

On HD1, the skidder made three drags before we could get to the back of the set where he was working. Also, while the skidder was working he made a short drag which was missed with the manual data collection because it was not on the same skid trail where he had been previously pulling bundles; this happened one more time on HD2.

On HD5 and HD6, some partial cycles were missed by the observer in the woods because the skidder headed in an unexpected direction. These elements were not missed by the GPS.

Table 8. The total number of skid cycles observed each half day of the study using each method of time data collection. The numbers of cycles observed are shown in conjunction with the actual number of cycles performed by the skidder.

Total Cycles		Cycles Observed	Actual Cycles
HD1	Manual	15	19
	GPS	19	
HD2	Manual	16	17
	GPS	17	
HD3	Manual	26	26
	GPS	26	
HD4	Manual	16	16
	GPS	16	
HD5	Manual	42	42
	GPS	42	
HD6	Manual	20	20
	GPS	20	

4. DISCUSSION

Statistically, the 1 second time interval was equally as accurate as the 5 second time interval for travel empty, grapple time, travel loaded, un-grapple time and total cycle time. The largest difference between the two time intervals was the amount of time it took to analyze the time data collected by the GPS and the ease at which one can analyze the time data.

Trail work is often difficult to record, especially when using the traditional method of collecting time data since most of the time trail work is performed between the set and the next load and is often done out of sight of the researchers. Trail work can be easy to pinpoint with GPS if the operator spends time on the trail going back and forth, but if the operator just slows down and drops slash on the trail and then continues it can be more difficult to collect using GPS. The more time that is spent on trail work the easier it is to collect with GPS.

<u>Travel Empty, Grapple Time, Travel Loaded, Un-grapple Time</u>

Differences between un-grapple times in 5 of six half days (HD's) were significantly different from zero. One of the reasons for this could be that the boundaries for the deck were not defined on half days 1, 2, 3 and 4. Also, deck time was frequently included in the un-grapple time with the manual data collection method, which was one of the main reasons why differences between un-grapple times were significantly different from zero.

Digital and physical boundaries can be set up on site in order to best determine when to start and stop travel loaded, un-grapple, haul slash and travel empty times. Digital boundaries could be included in the skidder line file by walking around the perimeter of the log deck before putting the GPS in the skidder cab, or by walking the perimeter of the set after the skidder has finished for the day. Creating a physical boundary around the perimeter of the set with flagging tape will help in collecting time data manually by showing the researcher a precise location where to stop and start different time elements

Even with un-grapple time broken down into smaller components such as delimbing, deck work and slash hauling, the differences between the two methods of time data collection were significantly different than zero in all of the half days of the study. In many instances, idle time on the deck or wait on loader time got included into the un-grapple with the manual data collection method. Using the manual data collection method, it was difficult to break up un-grapple time because the skidder would arrive on the deck, which would start the un-grapple time, but then stop as soon as it got close to the loader to wait for the loader to finish, which would start the idle time/wait on loader then quickly start moving to finish un-grappling. With the manual data collection technique there was often a lot of overlap between different tasks on the deck. Using GPS it was much easier to break up the time because the researcher could go forward and backwards along the GPS line file as needed and really get a good idea of when one task ended and another task began. Thus, GPS-collected data seems to be superior in this regard.

From looking at the results of this study for travel loaded and un-grapple it would be necessary to have someone stationed on the logging deck making notes of the times that different tasks started and ended to check the accuracy of the GPS times collected. The accuracy of travel loaded and un-grapple time could be greatly improved by using a combination of GPS and manual time data collection. However, this is still a big improvement over the manual time data collection technique because the observer stationed in the timber recording travel empty and grapple time is no longer needed, which is an important safety improvement as well as an economic improvement.

Haul Slash

Haul Slash was easy to recognize using GPS from skidder movements since the skidder wouldn't position to pick up a load and when the skidder returned to the deck there would be no un-grapple; most often, the skidder would go right around the deck and back down the normal skid trail where the bundles were laid out or would go straight back to cleaning the deck.

Looking For Logs Unsuccessfully

The task looking for logs unsuccessfully is more accurately collected when it is collected with a GPS receiver. The reason for this is that when you are in the field you do not notice that the operator was looking for logs unsuccessfully unless you can see all the way down the skid trail to know for yourself that there are no bundles at the end of the trail. Also, with GPS you are able to scroll back and forth between the points to get a more precise measurement of the amount of time the skidder operator spent looking for logs unsuccessfully. This is because when you are in the field the time is being recorded as travel empty until you make the realization the skidder operator is looking for logs. Then you stop travel empty and start time for the looking for logs time element; then you have to stop looking for logs when the skidder gets back on the correct skid trail and restart travel empty.

Total Cycles

One can accurately identify every skid cycle on each half day of the study using GPS and differentiate skid cycles from slash hauling off the deck. GPS allows one to measure skid cycles that were missed during the manual data collection as well as measure the lengths of drags made by the skidder. For total cycle time data, collecting data by GPS was easier, more cost effective, safer than and just as accurate as the manually collected data.

5. SUMMARY AND CONCLUSIONS

GPS is a good tool to use for collecting time data on trail work and looking for logs unsuccessfully because these elements of a time study on rubber-tired grapple skidders often go unseen when using the traditional method of collecting time data. The GPS times and manual times did not differ at $\alpha = 0.05$ on nearly all the tests. However, for travel loaded and un-grapple time, in all but one test, the difference between the two methods was significantly different. This can be contributed to digital and physical boundary errors as well as manual errors on the ground. Other time elements often were included into the un-grapple time such as idle time and deck work.

GPS is a good tool to use for deck work and haul slash times, but has some costs and benefits when it comes to collecting idle time data. The costs include the inability to see why the skidder is idle (such as maintenance work, waiting on the loader, directing traffic, etc.). The benefit for using GPS to collect idle time data is that the researcher can collect this time data quickly and efficiently without having to be present on site.

Differences between total cycle times for the two methods of data collection were found not to be statistically different than zero at $\alpha = 0.05$. GPS can be used accurately for collecting total cycle times on rubber-tired grapple skidders.

Line data was collected with GPS using a 5 second time interval between GPS points on Half Days 1-5 and a 1 second time interval between GPS points on HD6. The 1 second time interval data took twice as long to analyze as the 5 second interval data but was no more accurate. Since there were so many points collected with the 1 second time interval, the transition between tasks became blended and it was not as clear when the skidder was ending one task and starting another. Using the 5 second time interval, the transitions between tasks were more obvious, which made the analysis of the data more rapid.

The Trimble GeoXT with external antenna is a good tool to use for collecting time data on rubber-tired grapple skidders operating in second thin loblolly pine plantations. In fact a GPS unit could be used for a completely unattended time study of grapple skidders because the mistakes associated with the manual time data collection method and GPS method offset each other. Ideally a combination of 1 researcher plus a GPS unit could collect very accurate time data on rubber-tired grapple skidders operating on a second thin in plantation loblolly pine. The researcher should stay on the logging deck to record movements of the skidder since this is where there were the most differences between the traditional methods for collecting time data and GPS. GPS has shown to be a very useful tool in collecting time data on trail work, travel empty, grapple time, searching for logs unsuccessfully, idle time and deck time. A researcher would be needed to make notes on haul slash, travel loaded, un-grapple time and deck work, as well as make notes on why the skidder is idling in order to check the accuracy of the GPS. Also, line data collected on a 5 second time interval is easier and quicker to analyze that line data collected on a 1 second time interval, without sacrificing accuracy.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Evaluation of a Cut-to-Length System Implementing Fuel Reduction Treatments on the Coconino National Forest in Arizona*

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Abstract
A Cut-to-Length (CTL) system was evaluated for production and cost while implementing fuel reduction treatments in two stands on the Coconino National Forest in Arizona. Product recovery and fire behavior within each stand after treatment were also examined. Only trees less than 16 inches diameter breast height (DBH) were harvested. After logs were forwarded to a landing, the remaining slash in each stand was removed by the forwarder for fire hazard reduction. Time-and-motion data collected revealed the harvester produced 364 cubic feet (cf) per Productive Machine Hour (PMH) while harvesting sawlogs and 33 cf per PMH while harvesting biomass. Forwarder productivity averaged 690 cf per PMH while transporting sawlogs and 160 cf per PMH while transporting biomass. System cost, with profit and overhead, was estimated at $208 per Scheduled Machine Hour (SMH). Unit costs were $0.88 per cf while harvesting sawlogs and $9.62 while harvesting biomass.

1. INTRODUCTION

Decades of fire exclusion and little active management have resulted in millions of acres of National Forest land in the western U.S. with high fuel loads. These forests contain accumulations of flammable fuel that are much higher than historical conditions (Peterson, et al. 2005). These high fuel loads add to the potential for catastrophic wildfires.

The Coconino National Forest entirely surrounds Flagstaff, Arizona. Approximately 600 wildland fires occur annually in the greater Flagstaff area and about 60 percent of those are caused by lightning (http://www.gcfp.org/firerisk.htm.). From 1970 to the present, an average of 2900 acres burn each year in the area, and a majority of these acres burned catastrophically (http://www.gcfp.org/firerisk.htm.).

The cost associated with removal of fuel load, whether mechanically or through prescribed fires, is high. Historically, the types of small-diameter trees removed in fuel reduction treatments were considered non-merchantable and treated as slash or waste. However, this material should be removed because it can substantially increase fuel loading or attract insects that can subsequently kill remaining trees (Six et al. 2002). However, removal requires either better utilization or costly disposal.

The objectives of this study were to assess the economic and ecological costs and benefits associated with the harvesting and utilization of fuel reduction treatments and to evaluate in-woods decision-making regarding tree selection, residuals left on site, product suitability, and market opportunities. This paper addresses harvesting costs and productivity associated with performing fuel reduction treatments using a Cut-to-Length (CTL) harvest system.

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 405-414.*

2. STUDY AREA

The study area was located on the Coconino National Forest near Flagstaff, Arizona and was comprised of two units, each totaling approximately 20 acres in size with ponderosa pine as the dominate tree species. The sale was prepared by marking the residual trees or a leave tree mark (LTM). Terrain was relatively gentle but rocky. Unit 1 had a pre-harvest density of 179 trees per acre (Figure 1) and a quadratic mean diameter (QMD) of 10.2 inches. The prescription called for removal of 105 trees per acre of trees less than 16 inches DBH resulting in 29 percent reduction in basal area. Volume removed totaled 3.98 hundred cubic feet (CCF) per acre for Unit 1 (Figure 2). Unit 2 had a pre-harvest density of 544 trees per acre (Figure 3). Trees were smaller with 57 percent of stems in the 1 to 4 inch DBH class and an initial QMD of 6.4 inches. The prescription was to remove approximately 451 trees per acre with a 56 percent reduction in basal area. Volume removed from Unit 2 totaled 8.03 CCF per acre (Figure 4).

3. HARVEST SYSTEM

The CTL system was comprised of a Timberjack[1] 1270 harvester and Timberjack 1010B 10-ton forwarder. The harvester was powered by a 204-hp engine and was equipped with four Nokia 700/50-25.5 tires on the front and two Nokia 700/55-34 tires on the rear. The forwarder was powered by a 110-hp engine. Products included firewood, sawlogs, and vigas. Vigas are logs used as rafters left exposed for aesthetic purposes in Southwestern homes.

4. METHODS

4.1 Stand Inventory

Prior to harvest eight 0.1-acre circular plots were installed on a grid within each study area. Within each plot DBH and total height were recorded for each tree along with a code indicating whether it was a cut or leave tree. Trees less than 18 inches DBH were measured to the nearest 0.1-inch using calipers and larger trees were measured with a D-tape. Tree heights were measured to the nearest 0.5-ft using a hypsometer. A numbered card was attached to each cut tree within a plot to account for volume cut during data collection. Percent slope and level of rockiness (low, med, high) were also recorded for each plot.

4.2 Harvest System

Production data were collected on each machine to estimate the machine production rate (volume per hour). The cost per hour and the production estimate were used to calculate cost per unit. The harvester was recorded on videotape as it cut through each study plot. The camera

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[1] Reference herein to any specific commercial products, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government.

operator called out tree numbers as they were cut. To obtain additional detailed production data on the harvester, the harvest of trees outside of measured plots were also recorded on videotape. These trees were tagged for another aspect of the study and DBH and total height were known. The diameter of surrounding non-tagged trees to be cut were measured and verbally recorded as they were cut. The harvester felled and processed trees at the stump into either sawlogs, vigas, or firewood. Regression analysis was used to determine the effect of tree size on time per tree.

Since Unit 2 had a large number of trees per acre in the 1 to 4 inch class, a feller-buncher was used to cut trees in this size class. The harvester was then utilized to cut and process more merchantable material.

For both units the forwarder hauled wood to roadside for loading onto trucks. Its productivity was measured using stopwatches to record cycle times. Elements recorded within a cycle included travel empty, load, intermediate travel, travel loaded, and unload. Regression analysis was used to determine the effect of haul distance on cycle time. Delays which occurred during a cycle were also measured and noted. Turn volume was estimated by classifying pieces as either large or small and estimating mean volume for each class size. The mean volume was estimated by measuring a sample of cut pieces throughout the unit prior to forwarding. Measurements of large and small end diameter, mid-point diameter, and length were collected on a sample of 155 pieces (Table 2). Volume of each piece was calculated using Newton's formula. To determine the cost of using the forwarder to haul slash from the site to roadside, forwarder bunk size was measured and a packing ratio of 0.1 (PNW GTR-364) was used to yield an estimate of solid wood volume (oven-dry) per cycle. This was done on only 10 acres of the unit.

5. RESULTS

5.1 Stand Inventory

Inventory data from the study site showing initial, cut, and residual stand density and volume per acre are displayed in Figures 1 through 4 below. In Unit 1 only trees less than 16 inches DBH were harvested which yielded a residual QMD of 13.4 inches and residual basal area of 71 ft^2 per acre. Residual QMD for Unit 2 was 10.4 inches with a residual basal area of 54 ft^2 per acre.

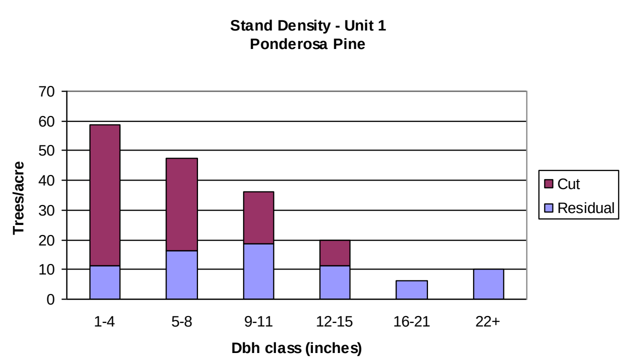

Figure 1. Diameter distribution for total, cut, and residual trees for Unit 1.

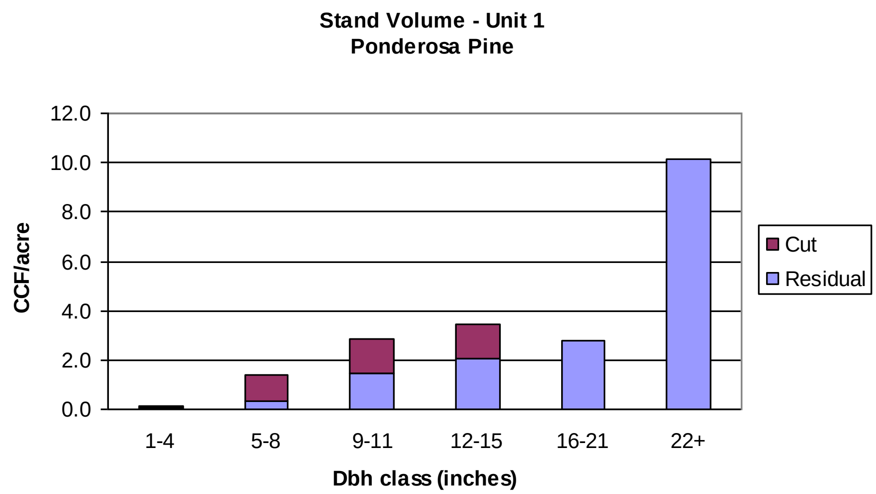

Figure 2. Total, cut, and residual volume per acre by diameter class for Unit 1.

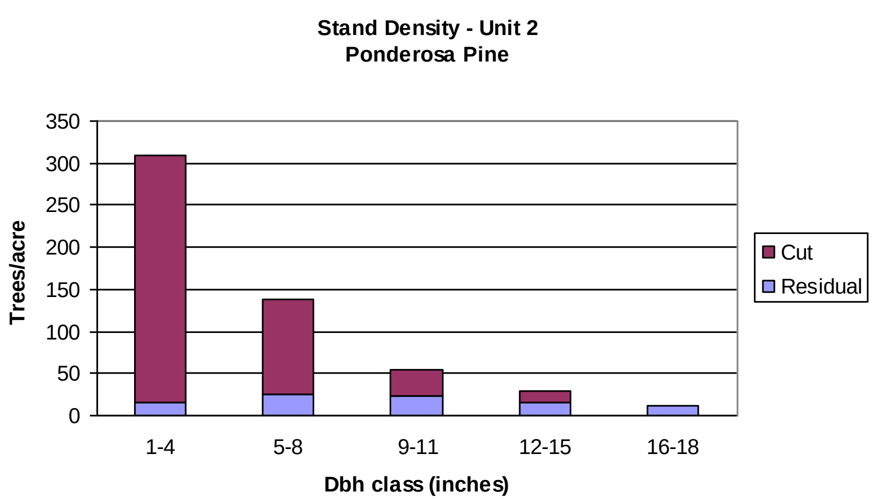

Figure 3. Diameter distribution for total, cut, and residual trees for Unit 2.

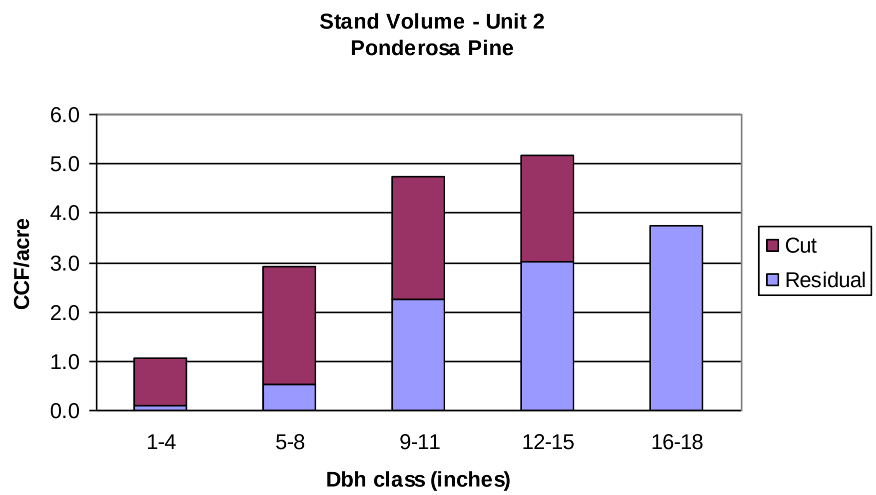

Figure 4. Total, cut, and residual volume per acre by diameter class for Unit 2.

5.2 Harvest System

5.2.1 Harvester

An unusually high number of delays were observed for the harvester while working thru the stand. A total of 60 delays were encountered during the 9-day period. Of these 22 (37%) were saw related. In-shift delay time totaled 27.65 hours for the study period. Out-of-shift delay time totaled 3 hours. Sixteen hours of delay time were attributed to waiting on parts for the head to arrive. Figure 5 shows the total and percent of delay time by category. Waiting repair time included machine down time due to waiting on parts to arrive. Active repair time consisted of repairing hose leaks, replacing thrown chain back onto bar, sharpening chain, and working on rollers. Service time included fueling, replacing bar, and replacing chain. Non-mechanical delays included removing hung bar, measuring logs for length, talking, and other miscellaneous occurrences. Personnel time included breaks and lunch.

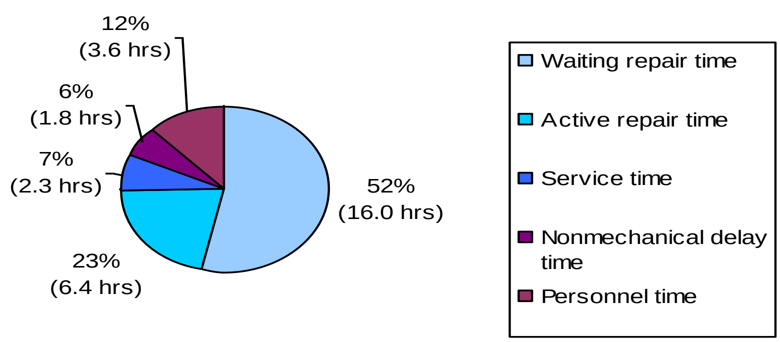

Figure 5. Breakdown of harvester delays by category.

The effect of DBH on cost per cf is shown in Figure 6. Harvesting trees in the 3 to 5 inch DBH class is very cost prohibitive. Cost per unit decreases dramatically for trees above 5 inches DBH.

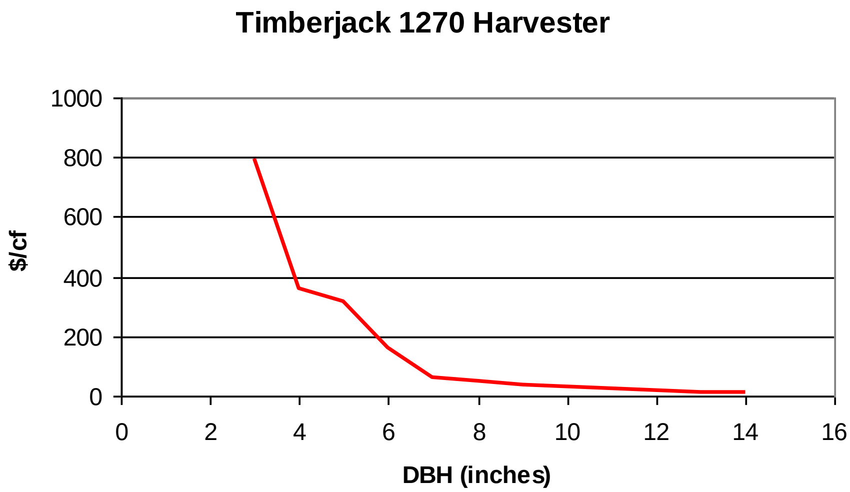

Figure 6. Effect of tree diameter on unit cost.

Gross time study data revealed that the harvester operated slightly over 24 hours of productive time, treated 17.6 acres, and harvested 1306 trees. This resulted in a production rate of 54.3 trees per hour, or 0.73 acres per hour. Analysis of detailed time study data from study plots revealed a production rate of 364 cf per PMH. General Linear Models procedure (SAS 1988) showed that DBH squared ($p < 0.0001$) was the most significant variable that influenced time per tree.

$$\textit{Time per tree (sec)} = 24.796 + 0.31419 * Dbh^2$$

$n = 138$; $R^2 = 0.50$

Time per tree included move, swing, cut, fell, and process elements. Processing included cutting products from the tree, delimbing, and topping. The relationship between DBH and time per tree is illustrated in Figure 7.

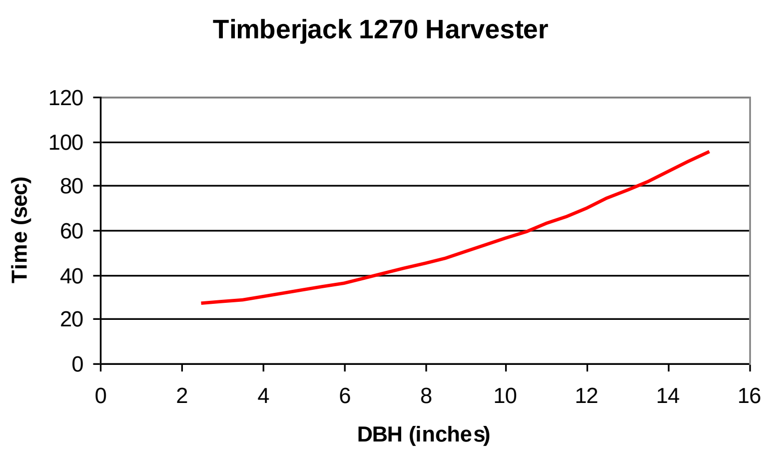

Figure 7. Predicted harvester cycle time for the range in DBH.

The harvester cut trees that ranged from 2.2 to 15.1 inches DBH. Mean DBH was 7.76 inches. A summary of time study variables for the harvester is shown in Table 1.

Table 1. Summary of elementary statistics for the 1270 harvester.

Variable	***N***	***Mean***	***SD***	***Min***	***Max***
Move (sec)	60	18.6	9.35	3.6	44.0
Move per tree (sec)	138	8.3	7.68	1.5	39.4
Reach (sec)	137	11.8	6.23	2.2	36.9
Fell (sec)	138	8.2	5.21	2.5	33.2
Process (sec)	138	13.9	15.75	0	98.9
Pile (sec)	109	5.0	2.15	1.1	14.8
Time per tree (sec)	138	46.1	21.60	18.2	149.8
No. of cuts	138	1.3	0.59	0	2
DBH (in)	138	7.8	2.77	2.2	15.1
Total height (ft)	138	37.6	9.38	10.0	62.5
Volume per tree (cf inside bark)	138	5.0	4.76	0.1	25.9
Productivity (cf per PMH)	138	363.5	272.30	14.3	1396.4

5.2.2 Forwarder

Elements evaluated for the forwarder included travel empty, travel loaded, intermediate travel, load, and unload. For the two units combined, one-way travel distance averaged 816 feet. The forwarder averaged 6.2 CCF per load of solid product which resulted in a mean productivity of 6.7 CCF per PMH. One-way distance for transporting slash averaged 157 feet. Table 3 summarizes elementary statistics for the variables measured.

Table 2. Elementary statistics for piece measurements.

Variable	***N***	***Mean***	***SD***	***Min.***	***Max.***
Large end diameter (in)	155	10.4	2.82	4.6	19.5
Mid-point diameter (in)	155	8.2	2.05	3.8	16.0
Small end diameter (in)	155	6.7	1.94	2.7	12.4
Length (ft)	155	19.1	3.57	10.0	30.0
Volume (cf)	155	8.0	4.69	1.4	27.2

General Linear Models procedure (SAS 1988) was used to develop regression equations for predicting elemental time for each dependent variable while hauling wood. Travel empty and loaded times were combined in the analysis into a total travel time. Total travel distance was the most significant independent variable affecting travel time ($p < 0.0001$). For intermediate travel time load volume ($p = 0.0132$) and total number of pieces loaded ($p = 0.0218$) were the most significant independent variables. Load time was a function of the inverse of the number of swings to load ($p = 0.0012$). For unloading, the mean unloading time was the best estimator. Regression equations for the above mentioned variables are shown below. The effect of total travel distance on cost per CCF for the forwarder hauling sawlogs is shown in Figure 8.

Table 3. Summary of elementary statistics for the 1010B forwarder.

Variable	***Sawlogs***					***Biomass***				
	N	**Mean**	**SD**	**Min**	**Max**	**N**	**Mean**	**SD**	**Min**	**Max**
Trv. empty (min)	22	5.1	4.57	0.6	17.3	15	1.6	2.43	0.3	10.1
Int. travel (min)	23	7.9	5.13	0.9	18.5	15	4.9	2.16	0.8	8.6
Load (min)	23	24.4	6.08	14.5	35.0	15	15.6	4.98	7.6	28.1
Trv. loaded (min)	22	6.4	3.76	0.5	13.3	15	1.9	1.06	0.6	3.8
Unload (min)	22	13.2	4.65	4.9	24.1	15	2.6	0.84	1.1	3.8
Total time (min)	22	56.6	6.74	40.6	66.2	15	26.6	7.01	17.1	44.2
Load volume (cf)	23	619.3	187.59	313	1102	15	665.6	0.00	665	665
Productivity (CCF/PMH)	23	6.7	2.37	3.1	13.7	15	1.6	0.38	0.9	2.3
Trv. empty dist. (ft)	23	662.2	576.43	56	1770	15	110.8	71.40	32	280
Trv. loaded dist. (ft)	23	969.2	504.66	90	2001	15	204.1	134.64	45	543
Total dist. (ft)	23	1631.4	1001.68	295	3521	15	314.9	158.39	133	684
# pcs per load	23	71.8	15.71	46	116	-	-	-	-	-
# pcs per swing	23	2.4	0.70	1.8	4.8	-	-	-	-	-
# swings to load	23	30.7	5.51	22	43	-	-	-	-	-

*Travel time (min) = 1.4657 + 0.006102*TDist*
where TDist = sum of travel empty and travel loaded distances in feet
n = 23; r^2 = 0.74; C.V. = 32.60

*Intermediate travel time (min) = 1.128 + 0.02541*LoadVol – 0.2773*TotalPcs*
where LoadVol = load volume in cubic feet; TotalPcs = total pieces loaded
N = 23; r^2 = 0.27; C.V. = 57.57

Load time (min) = 47.157 – 678.01(1/Swings)*
where Swings = total number of swings to load
n = 23; r^2 = 0.40; C.V. = 19.75

Combining the previous equations and adding mean unload time resulted in the following equation for predicting total cycle time for the forwarder.

*Total time (min) = 62.951 + 0.006102*TDist + 0.02541*LoadVol –*
*0.2773*TotalPcs - 678.01*(1/Swings)*

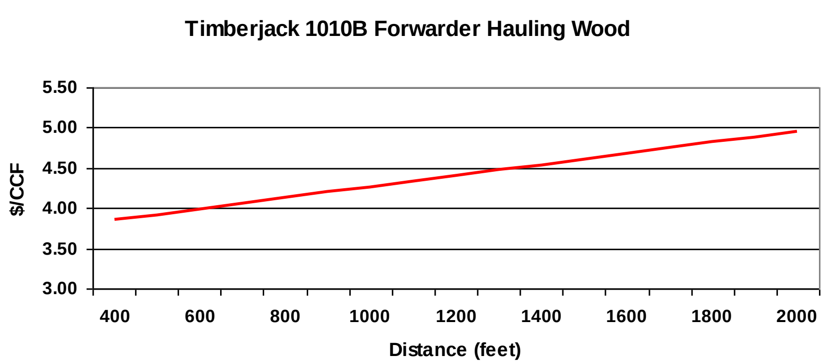

Figure 8. Effect of total travel distance on cost per CCF.

5.3 Costs

Machine costs were estimated using a machine rate analysis (Miyata, 1980), which reflects the average yearly owning and operating cost over the life of the machine. Ownership costs were estimated using a 5 year life, 20 percent salvage value, 10 percent interest rate, 4 percent of AYI for insurance and taxes, and 2000 scheduled machine hours (SMH) per year. Operating costs were estimated assuming a repair and maintenance rate of 110 percent of annual depreciation for the harvester and 100 percent for the forwarder, a fuel consumption rate of 0.02917 gal/hp-hr for the harvester, 0.02488 gal/hp-hr for the forwarder, a fuel cost of $2.15 per gallon, a lube cost of 36.8 percent of hourly fuel cost, and a utilization rate of 65 percent (Brinker, et al. 2002). A rate of $15 per hour was used for operator wage, plus 30 percent benefits. Profit and overhead were assumed to be 20 percent. Table 4 summarizes these costs for the two machines.

Table 4. Owning and operating costs for CTL machines.

Variable	***Harvester***	***Forwarder***
Purchase price ($ x 1000)	476	276
Salvage value ($)	85,250	55,250
Depreciation ($/yr)	68,200	44,200
AYI ($/yr x 1000)	290	188
Owning costs		
Interest ($/yr)	28,985	18,785
Insurance and taxes ($/yr)	11,594	7,514
Total Owning ($/SMH)	54	35
Operating costs		
Tires ($/PMH)	1.97	2.63
Fuel ($/PMH)	12.79	5.88
Lube and oil ($/PMH)	4.71	2.17
Repair & maint. ($/PMH)	57.71	34.00
Total Operating ($/SMH)	50	29
Labor & benefits ($/SMH)	19.50	19.50
Total Cost ($/SMH)[1]	124	84

[1]Includes 20% profit and overhead.

A comparison of system rates and costs for harvesting sawlogs and biomass are summarized in Table 5. Cost per cubic foot for handling biomass is eleven times more expensive than handling sawlogs.

Table 5. Cost summary for the CTL system.

	Productivity (cf/PMH)		***System Rate (cf/SMH)***		***System Cost***			
					Sawlogs		Biomass	
Machine	Sawlogs	Biomass	Sawlogs	Biomass	($/SMH)	($/cf)	($/SMH)	($/cf)
Harvester	364	33	237	22	208	0.88	208	9.62
Forwarder	690	160						

6. CONCLUSIONS

In the current system configuration, the harvester was the limiting machine while producing both sawlogs and biomass. While handling sawlogs, the forwarder could outproduce the harvester by about 2 to 1. With biomass, the difference was nearly 5 to 1. While small trees affected harvester more than forwarder productivity, both machines had significantly reduced output with biomass material. In fact, the cost per ton treated was nearly ten times greater for biomass than for sawlog products.

The most significant issue highlighted here is the inefficiency of using a single-grip harvester to handle small trees for a biomass product. Harvester productivity, on a volume basis, is greatly reduced as tree diameter decreases. In addition, the harvester logged less than 50 percent availability, mostly related to repairs on the harvester head. Given the high cost of treating smaller material with the CTL harvester, such treatments should carefully examine alternatives for the smallest material in a stand. These may include options such as leaving material in the unit, felling and bunching with a less costly machine, or mastication.

7. ACKNOWLEDGEMENTS

This project was supported by funding from the Joint Fire Science Program.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

A Productivity and Cost Comparison of Two Non-commercial Forest Fuel Reduction Machines*

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Abstract
Non-commercial forest fuel reduction activities can be defined as operations that change forest fuel structure without extracting fiber. Often known as masticating or mulching, the methodology chops, grinds, or chips small diameter understory trees and slash with a goal of redistributing ladder and/or surface fuel composition into finer fuels. Current non-commercial operations do not have the ability to extract trees/value and are considered management investments into the fire resiliency of a stand. To date, there has been practically no comprehensive research to study performance, cost, and silvicultural treatment effectiveness for non-commercial systems. This paper compares the productivity and cost generated from two different non-commercial equipment designs in a fuel reduction treatment. The machines were: 1) a swing-boom excavator (SBE) equipped with a rotary disc mulching head, and 2) a drive-to-tree flexible tracked machine (FTM) with a rotating drum mulching head. The study was conducted in an 80-acre uneven-aged ponderosa pine stand in central Oregon. The machines were restricted to a completely randomized split-plot experimental design and a common silvicultural prescription that employed spacing guidelines based on tree size. Shift-level time studies were used to determine machine productivity and cost per unit area and volume. Results indicate that productivity between the machines was significantly different (2.02 acres per day or 61% higher for the FTM). However, contrasting operating costs between machines allowed treatment costs per ton and acre to be comparable with no significant differences found. Cost projections averaged $311.39 per acre for the SBE and $348.89 per acre for the FTM.

1. INTRODUCTION

Forest managers currently have a small information pool for making sound decisions of equipment selection and silvicultural treatment effectiveness for fuel reduction activities (USFS 2005). There are numerous limitations and knowledge gaps for managers to select, plan, and implement appropriate technologies to meet sustainable forest management goals. Once treatment prescriptions are established, important factors including mechanical system productivity and cost, soil disturbance, and the projected fire behavior benefits must be assessed. Quantifying these variables is especially important when considering non-commercial options to modifying forest fuel structure.

Here, we define non-commercial fuel reduction activities as those with an end goal of changing forest fuel structure without extracting fiber. These systems represent the newest and most under-studied technologies for mechanical forest fuel reduction. To date, there has been

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 415-423.*

practically no comprehensive research to study such machinery with a fuel reduction objective. Studies, which have been completed, have failed to reach the literature or have been small-scale equipment trials to build baseline knowledge of the technology (Coulter et al. 2002).

In contrast to commercial harvesting systems, non-commercial ones do not actually remove trees from the forest. Graham et al. (2004) stated that these treatments "utilize machines to rearrange, compact, or otherwise change fire hazard without reducing fuel loads." There has recently been a surge of new technologies designed solely for non-commercial treatments or modified machine attachments designed for installation on existing equipment. Often known as masticating or mulching, the methodology chops, grinds, or chips small diameter understory trees and slash with a goal of redistributing ladder and/or surface fuel composition into finer fuels. With this approach, no fuel is actually removed from the forest, but when small trees are converted into finer fuels, wildland fires may burn less intensely and the possibility of stand replacement crown fires may also be reduced. Hartsough (2004) reported that "mastication uses horizontal or vertical axis flails or cutters to chop small diameter trees and brush in the understory". USFS (2004) indicated that "converting 20 tons per acre of understory biomass into small pieces should produce a uniform layer about 1-inch deep across the stand".

Most purpose built machines consist either of small skid steering rubber-tired or tracked carriers equipped with a front or rear mounted masticating/mulching head. Also, traditional flexible tracked drive-to-tree skidding machines are being tested with masticating/mulching heads. In addition, attachments exist for traditional rubber-tired drive-to-tree machines or excavator based swing-boom machines. Without the ability to extract trees from the forest no revenue is generated and current non-commercial systems should be considered as management investments into the fire resiliency of a stand. USFS (2005) reported a broad range non-commercial treatment cost to be $100 to $1,000 per acre. Recent inquiries of equipment manufacturers have yielded estimated treatment costs of $300 to $600 per acre.

In addition to the knowledge deficiency concerning treatment cost, no known numbers have been reported on the effects of non-commercial fuel reduction treatments. Important factors such as residual stand damage, soil disturbance impacts, or the size and composition of the resulting masticated fuel must be investigated to facilitate decision making. This lack of information creates challenges for forest managers charged with designing and implementing fuel reduction activities.

This paper compares the productivity and cost of two non-commercial machines employed in a fuel reduction treatment of an 80-acre ponderosa pine (*Pinus ponderosa*) stand in central Oregon. The machines were (Figure 1): 1) a swing-boom excavator (SBE) equipped with a rotary disc mulching head, and 2) a drive-to-tree flexible tracked machine (FTM) with a rotating drum mulching head. The specific research question was: what level of productivity and cost, per unit volume and area, can be expected from each of the machines?

Figure 1. Caterpillar[1] 315CL swing-boom hydraulic excavator equipped with an advanced forest equipment RDM 9044EX rotary disc mulching head (left), and KMC 2100H drive-to-tree flexible tracked hydrostatic mulcher equipped with a Fecon Bull Hog 120H-2 rotating drum mulching head (right).

2. METHODS

2.1 Study Site and Silvicultural Prescription

This study was conducted during the summer of 2004 in central Oregon on the Confederated Tribes of the Warm Springs Indian Reservation (WSIR), approximately 20 miles west of Warm Springs, Oregon. The site was chosen by the landowner who was interested in gaining more information on the productivity and cost of non-commercial forest fuel reduction operations. The 80-acre site consisted primarily of ponderosa pine (30-120 years old) with excessive understory regeneration. Site conditions include gentle slopes averaging 3.5% (min 1.5%, max 6.5%), an aspect of 40º, and elevation of 2,800-3,000 feet. In addition to the ponderosa pine, there are a few Douglas-fir (*Pseudotsuga menziesii*), western juniper (*Juniperus*

[1] The use of brand or model names is for reader convenience only and does not represent and endorsement by the authors or Oregon State University.

occidentalis), and incense-cedar (*Calocedrus decurrens*) scattered throughout the stand. The plant community is classified as PIPO/PUTR-ARPA (ponderosa pine), bitterbrush (*Purshia tridentata*), and green-leaf manzanita (*Arctostaphylos patula*) (Marsh et al. 1987). Understory shrubs ranged in age from 30-40 years old (Arena 2005) and height up to 5 feet. Vertical stand structure is such that ladder fuels may cause a non-lethal fire to become catastrophic and stand replacing. Results from the 2004 pre-treatment stand exam are displayed in Table 1.

Table 1. Pre-treatment stand exam statistics (per 5-acre subunit). N=16.

	Mean	SD	CV (%)	SE	95% CI	%SE
Trees/acre	443.70	231.05	52	57.76	320.58-566.82	13
Basal area/acre (ft^2)	66.27	17.03	26	4.26	57.20-75.35	6
SDI	126.73	31.86	25	7.96	109.75-143.71	6
QMD (inches)	5.74	1.56	27	0.39	4.90-6.57	7

The stand is uneven-aged with an inverse J-shaped diameter distribution. Ninety-five percent, or 423, of the total trees per acre are in DBH classes ≤ 10 inches. The remaining overstory consists of a few large-diameter trees greater than 10-inches DBH, approximately 20 per acre. Suppressed and co-dominant crown classes contribute the greatest number of trees. The 10-inch DBH class contains 9.3 ft^2 of basal area per acre, which is more than any other class. Large-diameter trees, >20-inches DBH, contain only 12.1 ft^2 of the total stand basal area per acre, or 17%.

The objective of the silvicultural prescription was to reduce the risk of catastrophic wildfire by mechanically masticating/mulching shrubs, standing dead and suppressed live trees, and redistributing down woody fuel into the 100-hr fuel category or less. Standing trees <8 inches DBH in the sapling/pole sized clumps were thinned to 16 by 16 feet. In the greater than or equal to 8 to 12-inch DBH clumps, residual trees were spaced to 22-feet. Due to management restrictions, no trees ≥12-inches DBH were treated. Tree stumps were not left any lower than 2-inches or higher than 6-inches above the ground level, a boulder, or other unmovable object. Leave tree characteristics were: 1) disease free, 2) dominant or co-dominant, 3) ≥30% crown ratio, 4) dense crown, 5) good form with no forking, and 6) good terminal leader growth. In addition, all down woody fuel, whether from treated standing trees or existing down trees, was masticated to a residual size no greater than 3 inches in diameter and 3 feet in length. The resulting masticated/mulched material was left no higher than 1 foot above the forest floor. All live and dead shrubs taller than 6 inches above the ground surface were also masticated throughout the stand.

2.2 Experimental Design and Data Collection

Standing trees, understory shrub percent cover, and down woody fuel composition were recorded before and after treatment. The difference between pre and post treatment measurements determined the machine treatment effect. The 80 acre stand was systematically divided into 16, approximately 5-acre subunits. Eight subunits were randomly assigned to each machine to perform the silvicultural prescription and ranged from 4.3-6.1 acres in size with an average of 5.2 acres. By machine type, SBE subunits averaged 5.1 acres and FTM subunits averaged 5.3 acres in size.

During the study, all SBE subunits were treated by the same operator. The operator had more than 1,000 hours of experience performing forest fuel reduction silvicultural prescriptions in several states throughout the Western U.S. Due to the experience level, no trees were marked by the research team. Operator selection of both trees and down woody fuel for treatment was used for all SBE subunits. Periodic walkthrough exams were performed to ensure that prescription requirements were met. Any necessary modifications were then relayed to the operator.

As for the SBE, all FTM subunits were treated by the same operator. It is important to note that the KMC/Bull Hog combination was a prototype machine with less than 200 hours of working time. Therefore, the operator was relatively inexperienced with the machine prior to the study. The machine had been used for clearing right-of-ways and installing defensible strips but no forest fuel reduction thinning prescriptions had been implemented. In support, an additional crew member (spotter) was used to mark leave trees and any significant obstacles such as rock outcroppings or sensitive areas. Along with the research team and landowner representatives, the spotter was trained on tree marking techniques and spacing guidelines. Periodic walkthrough exams were performed to ensure that prescription requirements were met and any necessary modifications were then relayed to the operator and spotter. Members of the research team inspected each subunit for prescription compliance before any further work.

Machine performance was assessed using shift-level information provided by operators. Each operator was asked to complete and submit productivity forms at the end of each work day. New shift-level forms were started at the beginning of each work day and/or when treatment began in a new subunit. Requested data included general information such as: date, subunit number, start time, end time, weather conditions, and delays >5 minutes. Delays were defined as any activity, lasting longer than 5 minutes, that was not part of the productive cycle necessary to complete the silvicultural prescription. Shift-level data provided gross productivity information such as machine utilization, hours per acre, and acres per day.

2.3 Data Analysis

Gross level productivity of the fuel reduction machines was estimated by compiling shift-level forms. Data was analyzed on a subunit basis and included scheduled machine hours (SMH) and delays >5 minutes. Subtracting delay time from SMH gave each machine's productive machine hours (PMH) and resulting utilization. Using subunit area, determined by a global positioning system, hours per acre and acres per 10-hr day were calculated. To estimate productivity on a per unit volume basis, total above ground biomass treated was estimated with equations from Jenkins et al. (2004). The difference between pre and post treatment total above ground green tons per acre (all trees) determined the weight of standing trees treated. One-way analysis of variance (ANOVA) was used to determine differences in subunit productivity means, per unit area and volume, between the machines. For all tests, statistical significance was determined at the α=0.05 level.

Based on information collected during the shift-level productivity study, costs were predicted using the Auburn Harvesting Analyzer (AHA) spreadsheet model (Tufts et al. 1985). The spreadsheet is capable of determining the productivity and unit cost for a treatment area based on the type of equipment used, the size of trees treated, and other operational variables. One AHA spreadsheet was constructed for each machine. Spreadsheet output included treatment costs per green ton and acres treated for each machine and subunit combination. Each spreadsheet produced unique values that were used to calculate mean costs per subunit. One-way ANOVA was then used to estimate differences in cost means between the machines.

Detailed input assumptions for each AHA spreadsheet are outlined in a separate report by Bolding (2006).

3. RESULTS AND DISCUSSION

The difference between pre and post treatment stand measurements determined the number of trees, standing green tons, and density removed during treatment. Table 2 shows mean stand density and biomass statistics per subunit treated for each machine. The similarity in values between machines indicates that each operator performed the treatment as prescribed in regard to standing trees. The largest difference in the means was residual trees per acre (73.96 for the SBE vs. 58.86 for the FTM).

Table 2. Stand density and biomass statistics. N=8/machine.

	Pre-treatment	Treated	Residual
SBE			
Trees per acre	447.45	373.49	73.96
Green tons per acre	55.57	15.18	40.39
Basal area per acre (ft^2)	64.40	23.63	40.77
Stand density index (SDI)	124.91	58.03	66.88
FTM			
Trees per acre	439.95	381.09	58.86
Green tons per acre	59.21	20.91	38.29
Basal area per acre (ft^2)	68.14	29.01	39.12
Stand density index (SDI)	128.56	66.29	62.26

3.1 Machine Productivity

Descriptive statistics from the shift-level productivity study are shown in Table 3 along with one-way ANOVA results in Table 4. Results from operator supplied shift-level forms indicate statistically significant differences between the machines in SMH per subunit and acre, PMH per subunit and acre, acres treated per 10-hr day, and standing green tons treated per PMH.

Table 3. Shift-level productivity descriptive statistics[1]. N=8/machine.

	SBE				FTM		
	Mean (SD)	Min.	Max.		Mean (SD)	Min.	Max.
SU area (ac)	5.12 (0.56)	4.30	5.70		5.27 (0.51)	4.50	6.10
SMH / SU	15.71 (1.82)	13.58	18.73		10.21 (1.87)	7.00	12.25
Delay time (hrs) / SU	0.96 (0.53)	0.43	1.70		0.91 (0.57)	0.00	1.58
PMH / SU	14.75 (1.81)	12.07	17.30		9.30 (1.32)	7.00	10.83
Utilization (%)	93.88 (3.46)	87.65	97.41		91.85 (4.75)	86.81	100.00
SMH / ac	3.10 (0.49)	2.43	3.90		1.94 (0.35)	1.40	2.35
PMH / ac	2.91 (0.47)	2.33	3.79		1.77 (0.27)	1.37	2.13
Ac / 10-hr day	3.30 (0.53)	2.57	4.12		5.32 (1.10)	4.25	7.15
Green tons / PMH	5.28 (2.13)	1.80	7.87		11.66 (6.60)	2.17	23.77

[1]SD=standard deviation, SBE=swing-boom excavator, FTM=flexible tracked mulcher, SU=subunit, SMH=scheduled machine hours, PMH=productive machine hours.

In all significant categories, the FTM performed the prescription in less time than the SBE. The drive-to-tree design of the FTM allowed it to travel faster throughout the stand and resulted in more acres treated per day. For example, the FTM averaged 5.32 acres per 10-hr day versus 3.30 for the SBE. This difference of 2.02 acres per day or 61% may be of substantial importance for forest managers interested in treating large areas within limited schedules. The wide spacing prescription allowed the FTM to maneuver between large overstory leave trees while removing many small understory trees per machine pass. Tighter spacing requirements would likely favor the SBE due to the nature of machine design and resulting maneuverability advantage. Tradeoffs due to the more productive FTM may include increased soil disturbance due to the additional stand travel required.

Table 4. Shift-level productivity one-way ANOVA difference in means F and p values[1].

	F Value	Pr > F	Sig.
SU area (ac)	0.31	0.5858	
SMH / SU	35.48	<0.0001	√
Delay time (hrs) / SU	0.03	0.8545	
PMH / SU	47.39	<0.0001	√
Utilization (%)	0.95	0.3467	
SMH / ac	29.32	<0.0001	√
PMH / ac	34.73	<0.0001	√
Ac / 10-hr day	21.94	0.0003	√
Green tons / PMH	6.78	0.0208	√

[1]Sig.=significant difference between the machines at α=0.05, SU=subunit, SMH=scheduled machine hours, PMH=productive machine hours.

3.2 Treatment Costs

To estimate treatment costs, shift-level productivity results (green tons per PMH) were input into AHA spreadsheets for each machine/subunit combination. After combining productivity with green tons per acre treated, machine utilization, and operating costs, treatment costs per green ton and acre were calculated for each subunit. A cost summary and ANOVA significant differences between the machines is reported in Table 5.

Table 5. Mean (SD) treatment cost per subunit for each machine and combined cost irrespective of machine. Values in the same row with different superscripts are significantly different ($p<0.05$)[1].

	SBE[2]	FTM[2]	Combined[3]
Treatment cost			
$/green ton	24.97[a] (14.83)	27.74[a] (28.11)	26.35 (21.76)
$/acre	311.39[a] (49.81)	348.89[a] (57.79)	330.14 (55.60)

[1]SD=standard deviation, SBE=swing-boom excavator, FTM=flexible tracked mulcher.
[2]N=8, [3]N=16.

Mean treatment cost per green ton was estimated to be $24.97 for the SBE and $27.74 for the FTM. ANOVA indicated no significant difference between the two means ($F=0.06$, $p=0.8092$). Cost per ton by subunit for the SBE ranged from $13.92 to $58.72, whereas the range for FTM costs was $8.35 to $93.09. Subunits with the highest cost per ton projections were those that contained a large proportion of understory shrubs and relatively few trees per acre treated. In this case, machine productivity per unit volume was low and therefore costs were distributed over fewer tons of trees treated. After combining all subunits, irrespective of machine, overall treatment cost averaged $26.35 per green ton treated.

Costs per acre were generated by multiplying costs per ton by the number of tons per acre treated in each subunit. Average treatment cost per subunit was estimated to be $311.39 per acre for the SBE and $348.89 for the FTM with no significant difference detected ($F=1.93$, $p=0.1862$). Costs per acre ranged from $246.62 to $399.45 for the SBE and $260.53 to $414.07 for the FTM. When all 16 subunits were combined, average cost per acre was projected to be $330.14.

Although productivity between the machines was significantly different (2.02 acres per day or 61% higher for the FTM), contrasting operating costs allowed treatment costs per ton and acre to be comparable. Operating costs for the SBE averaged $70.65 per SMH whereas average costs for the FTM were $135.98 per SMH. This difference of 92% is largely due to machine purchase price. New prices were used for each machine and were $168,000 for the SBE and $493,750 for the FTM. In addition, due to operator inexperience, an additional crewmember (spotter) was necessary for the FTM which also increased hourly costs. Had the spotter not been required, average treatment costs for the FTM would have been reduced to $26.12 per green ton and $328.49 per acre.

4. CONCLUSIONS

Results from this study establish baseline information on the newest approach to mechanically reducing forest fuels. Two different non-commercial machine designs were compared in controlled trials that provided insight on the relative strengths and weaknesses of each machine. Cost results showed no significant difference in either cost per ton or acre between the machines. Even though the FTM was significantly more productive, a higher initial purchase price and resulting operating costs allowed treatment costs to be similar between the machines. Also, the use of a spotter for the FTM increased operating costs. It is unclear as to whether the additional crew member had an effect on productivity.

These results highlight important tradeoffs that should be considered when selecting equipment for forest fuel reduction treatments. Non-commercial machines provide no ability for fiber removal or utilization and should be considered a management investment into the fire resiliency of a stand. Productivity, cost, machine effectiveness, and site impacts must each be considered to ensure success from both an economically and ecologically sustainable perspective. For example, this study found that the most productive machine may not be the most cost effective machine. Other studies in progress are examining soil disturbance and fire altering effectiveness of the treatments (Bolding 2006). These combined factors will provide more comprehensive information to forest managers charged with implementing such prescriptions.

It is important to note that this study investigated one machine in each of two broad categories of equipment design: 1) drive-to-tree, and 2) swing-to-tree. This approach was taken to build baseline information for each design category. To gain more precise estimates of productivity and cost, future studies should investigate multiple machines within a design category over a range of stand and prescription requirements. In addition, the FTM was a prototype machine with less than 200 hours of operating time and even less performing thinning prescriptions. Although unproven, a more experienced operator may have resulted in less variation in productivity estimates. Further studies designed to compare the performance of multiple operators would provide insight on the relationship between operator experience and resulting productivity and cost.

Productivity estimates were generated from operator supplied shift-level forms which are only as accurate as the data provided. To establish more detailed information on machine operating patterns and economic feasibility, future studies should investigate machine productivity using detailed time and motion studies. Such an approach could be useful for establishing productivity estimates in terms of time per tree for a series of time elements. Producing regression models from elemental time studies will provide the forest manager with information that could be distributed throughout a proposed silvicultural prescription and used to make more informed decisions concerning machine performance over a range of alternatives. Given the lack of available productivity and cost information concerning non-commercial fuel reduction, there is a great opportunity for further research in the area.

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Harvesting Forest Biomass by Adding a Small Chipper to a Ground-Based Tree-Length Southern Pine Operation*

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Abstract
We looked at the addition of a small chipper (Conehead 565) to a mechanized, tree-length system to also harvest tops, limbs, and understory (dbh 1-4 inch) biomass. Three replicates of three treatments were evaluated in a 33-year-old slash pine plantation on a flatwoods site in the lower coastal plain of Echols County, GA. Treatments included A – roundwood harvest only, B – roundwood harvest and chipping of limbs and tops, and C – roundwood harvest with chipping of limbs, tops, and understory. The site contained an estimated 7.7 tons per acre of understory biomass with an average dbh of 2 inches. Water oak, swamp bay, and red maple accounted for 73% of the stems. Roundwood production averaged 65.8 tons per acre and did not differ significantly across the three treatments. A load of chips was produced for every 18 and 5 loads of roundwood in Treatments B and C, respectively. There were significant differences in the chips produced between treatment B (3.8 tons per acre) and treatment C (10.8 tons per acre) at the 10% level but not at the 5% level. Harvest of understory stems did not significantly increase fuel consumption per ton in treatment C. Chips took twice as much fuel per ton to produce due entirely to the addition of the chipper. Chips averaged 50% moisture content (wet basis) when produced and lab results showed heat content values of 19.1 MJ/kg, comparable to other woody biomass. All chips were used in an electricity co-generation unit at a local OSB mill with satisfactory results. Nutrient removals from the site were relatively low with losses associated with Treatment B comparable to annual atmospheric deposition. Cost projections suggest that this method of producing chips can be competitive if no more than 10 loads of roundwood are harvested to produce a load of chips or at least one load of chips is produced daily.

1. INTRODUCTION

The southern USA currently has an abundance of pine pulpwood in many areas, reflected by stumpage prices that have not increased in real terms for years. In this market, landowners and forest managers often find it difficult to have thinnings of pine plantations performed at a time that maximizes the biological response to thinning. This soft market for small trees can also lead to more selective product specifications for pulpwood, leaving smaller trees in the woods after clearcuts and requiring site preparation steps to deal with these residual standing stems. With more limited use of fire and mechanical treatments as site preparation tools, dealing with residual material prior to regeneration is becoming more expensive and problematic. Additional markets for small stems that are currently unmerchantable and for residues such as limbs and tops could turn what is currently a cost item into a potential revenue stream for the forest

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 425-433.*

landowner and reduce the investment required for reforestation. This material could serve as a feedstock for biorefinery or biomass energy facilities.

Most southern harvesting systems move full trees or merchantable tree-length stems to roadside (Greene *et al.* 2001). These systems evolved during the 1970s when it was common for hardwood pulpwood to be left standing in the woods (no market) while a few pine products (pulpwood, chip-n-saw logs, and large sawtimber/plylogs) and one hardwood log product were typically handled. During the late 1970s several projects examined ways to modify the tree-length systems of that time to allow them to recover forest biomass and smaller stems for energy (Puttock 1987, Miller *et al.* 1987, Watson *et al.* 1986, Stuart *et al.* 1981). All four studies identified the need for a single felling and skidding pass to collect both merchantable and residual material. Making two passes across the site – one to collect conventional products and a second to collect forest residues – was too expensive then and remains so today.

Today's product markets and logging equipment are quite different from those observed during the 1980s. For example, Watson *et al.* (1986) defined a "conventional" harvest as one that removed all pine 6 inches or greater and all hardwood 12 inches and greater in diameter. This implied no market at all for hardwood pulpwood while in today's market hardwood pulpwood often commands a higher price and enjoys more stable demand than pine pulpwood. The logging systems they examined did not employ sawhead feller-bunchers, used much smaller grapple skidders (measured by either horsepower or grapple size), did not evaluate mobile log loaders, and did not observe mechanized delimbing (pull-through delimbers, chain flails, or grapple processors) at the landing. All of this equipment is common today in southern forests.

The objective of this study was to use today's harvesting equipment to capture the smaller stems and harvesting residue that we typically leave in the woods after using tree-length systems. We were interested in how the addition of a small chipper to a tree-length operation would affect weekly production and delivered cost per ton of roundwood and chips. We also wanted information about the quality of the chips produced for use in a co-generation electricity facility at a forest products plant.

2. METHODS

This study was conducted cooperatively with Langdale Industries – a major privately owned forest products company – and Lott Logging Inc., one of their harvesting contractors. Lott Logging leased a Conehead 565 chipper during our study to evaluate its potential purchase. The Conehead 565 chipper has a 260 horsepower Cummins turbocharged diesel engine, a 21" diameter capacity, and a feed rate of 100 feet per minute. In addition to the chipper, Lott operated a Tigercat 718 feller-buncher, a John Deere 640D grapple skidder, and a Prentice 280 loader with a pull-through delimber. Lott typically performed thinnings, delimbed with a delimbing gate and the loader-mounted delimber, and set out loaded trailers for hauling by both owned and contract trucks. Their operation is very typical of ground-based, mechanized tree-length pine systems operated across the USA South.

The study location was a slash pine (*Pinus elliottii*) plantation on a flatwoods site in Echols County, Georgia that was 33 years old and had been thinned once. We divided the tract into 10 blocks (about 20 acres each) that would each take approximately five working days for Lott Logging to clearcut. Each block was randomly assigned one of three treatments. Treatment

A was the conventional ground-based tree-length harvesting system with no attempt to harvest limbs, tops, or unmerchantable stems. Treatment B was the conventional harvesting system with the addition of the Conehead chipper to chip all limbs and tops. Treatment C was the conventional system with the addition of the chipper to chip limbs, tops, and non-merchantable woody biomass of all species that was between one and four inches at diameter breast height (DBH) that could be harvested by the feller-buncher and skidder.

To estimate unmerchantable biomass we measured 0.05-acre circular plots that were located using a four chain by four-chain grid across each block. In each plot we tallied all unmerchantable stems that were defined as woody stems of any species with a dbh between one and four inches with a total height of at least eight feet. Species, dbh, and total height were recorded for each stem within a plot. We used weight equations to estimate total green weight tons of biomass (Franchi *et al*. 1984). We also used the USDA Forest Service photo series for quantifying natural fuels to assess the woody biomass available on the site (Ottmar *et al*. 2003).

From the 10 blocks, nine were randomly assigned a treatment (three replicates per treatment) and one was retained as a backup. The blocks were then harvested according to treatment. All the B's were cut first, followed by the C's, and last the A's. This sequence was used to minimize the time Lott needed to lease the chipper. Prior to cutting any of the study blocks, Lott used the chipper for a full working week on another tract to get accustomed to its use. Each study block assigned treatment A or B had a work sample collected during one full day of operation while treatment C blocks had two days monitored. Daily production in loads and tons was collected for each product class harvested on each block. Daily fuel usage and equipment operating hours were recorded for each piece of woods equipment. A 5-gallon chip sample was obtained from each study block and sealed for transport to a lab. A subsample of these chips were weighed and then dried to obtain moisture content, particle distribution, and bulk density. Chips were also evaluated to determine their elemental content (N, P, and K) and their potential heat content per unit of dry weight.

We estimated the cost of chips produced assuming the chipper cost $100,000 to purchase and was operated for 5 years with a residual salvage value of 20%. We assumed interest, insurance and taxes to be 9%, 6%, and 2 %, respectively. The maintenance and repairs cost are assumed at 100% of depreciation. Off-road diesel averaged $2.58 per gallon during our study. We also figured the chipper would have 90% availability. Chips were hauled from the woods at a cost of $0.12 per ton-mile. For Treatment B, chip cost per ton only included the cost of the chipper, loader costs associated with feeding the chipper, and trucking. For Treatment C, we also proportioned the cost of felling and skidding as this treatment required additional felling and skidding to perform.

3. RESULTS

Our inventory of the study blocks sampled an average of 16 plots in each block (Table 1). We found 220 stems per acre with an average DBH of 2.0 inches that comprised 7.7 tons per acre of understory biomass. Biomass estimates ranged from 4.9 to 11.4 tons per acre. Tallied species included water oak *(Quercus nigra)*, swamp bay (*Persea palustris*), red maple *(Acer rubrum)*, waxmyrtle (*Myrica cerifera*), slash pine, blueberry (*Vaccineum* sp.), yaupon (*Ilex vomitoria*), and titi (*Cyrilla racemiflora*). Water oak, sweet bay, and red maple together accounted for 73% of stems (Figure 1). Waxmyrtle, blueberry, yaupon, and titi are not commercial timber species, but the other species are commonly harvested when of acceptable size. USDA Forest Service methods for visually predicting fuel loads in a slash pine stand with similar understory species suggested that there would be 4.5 tons per acre of woody species with diameters of 4 inches or less. It also predicted that the forest floor load was 30.0 tons per acre.

Table 1. Inventory statistics and preharvest conditions of unmerchantable stems and underbrush of 1-4 inches DBH on 10 study blocks of 33-year old planted slash pine, Echols County, GA.

Block	Treatment	No. of Plots	Stems/Acre	Mean DBH (inches)	Biomass (tons/acre)
1	C	15	154	2.1	4.9
2	B	17	212	2.1	7.6
3	A	18	204	2.3	9.9
4	B	15	220	2.0	8.3
5	C	18	302	1.9	11.4
6	Spare	14	190	1.8	6.0
7	B	16	292	1.9	9.3
8	C	15	198	2.0	7.3
9	A	16	194	2.0	5.6
10	A	16	206	1.9	5.2
ALL		160	220	2.0	7.7

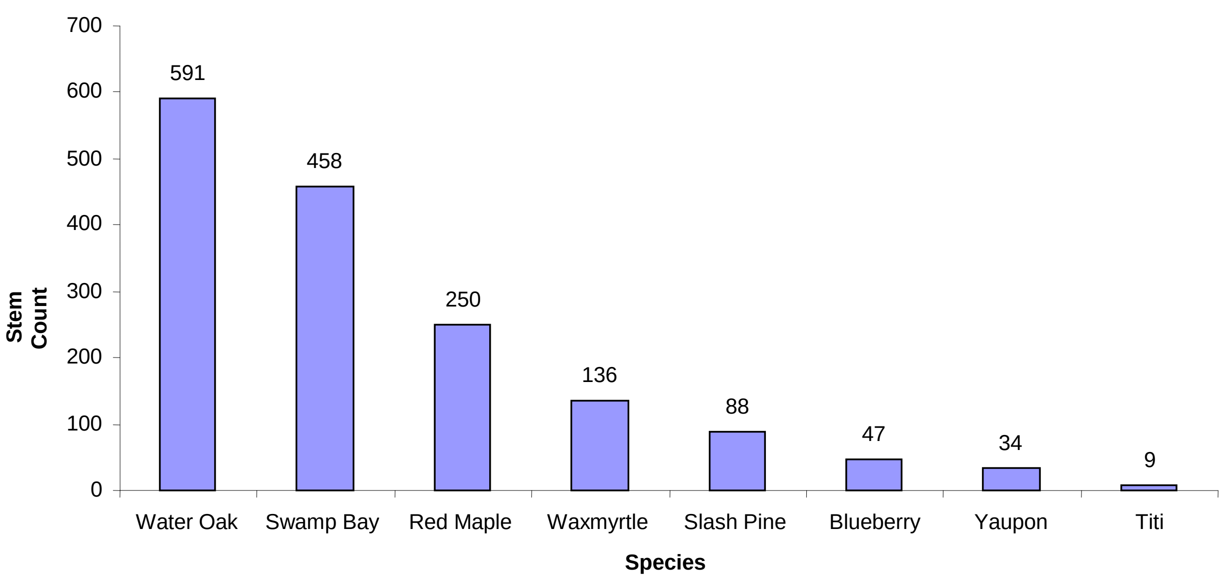

Figure 1. Frequency distribution by species of trees tallied in study blocks.

The amount of roundwood per acre produced by each treatment was not significantly different (Table 2). Treatment B also produced 3.8 tons of chips per acre compared to 10.8 tons produced by treatment C. These values were significantly different at the 10% level, but not at the 5% level. Treatment B used limbs and tops to produce chips while Treatment C used understory material as well. The difference between these two treatments – approximately 7 tons/acre – compares favorably with our preharvest estimates of available understory biomass (7.7 tons/acre). Production rates were similar across treatments with no significant differences found in hourly production (tons/SMH). The crew produced an average of 8 loads per day in the chipper treatments and 9 loads per day in the conventional roundwood treatments. The chips produced were an addition to the roundwood production and did not appear to significantly reduce roundwood production. A load of chips was produced for every 18 loads of roundwood in Treatment B and for every 5 loads of roundwood in Treatment C blocks. The roundwood to chip ratio for Treatment B would be closer to 12 if the results from block 2 were excluded where wet weather required use of some logging slash for an operating mat.

Fuel consumption (gallons per ton) of woods equipment (felling, skidding, and loading) was not significantly higher for the chipper treatments than the roundwood treatments (Table 3). Both conventional logging (Treatment A) and the chip treatments (B&C) consumed an average of 0.41 gallons of diesel per ton of wood produced for the felling, skidding, and loading activities. To produce a ton of chips also required another 0.40 gallons for chipping, thus a ton of chips required 0.83 gallons of diesel compared to 0.41 for a ton of roundwood.

Chips averaged approximately 50% moisture content as produced in the woods (Table 4). Lab analyses showed the chips to be primarily carbon with heating values comparable to those reported for other forms of woody biomass. One concern often expressed about utilization of logging residues involves nutrient removals from the site. Foliage and small limbs contain a disproportionate amount of nitrogen (N), phosphorous (P), and potassium (K). Our chip analyses indicated higher percentages of N, P, and K in chips from Treatment C than from Treatment B. Results from our chip analyses combined with the tons removed per acre suggest that in the most intensively harvested Treatment C blocks less than 24 lb/ac of N was removed. Removals of P and K were approximately 2.5 lb/ac and 7.1 lb/ac, respectively, in Treatment C. Treatment B nutrient losses due to biomass removal were estimated at 6.48 lb/ac of N, 0.52 lb/ac of P, and 1.73 lb/ac of K. Annual atmospheric deposition of nitrogen through rainfall and particulate matter is 5.9 lbs per acre per year (Boring *et al.* 1988). Carter *et al.* (2004) state that 0.36 lbs P and 1.5 lbs K are average annual inputs per acre.

The market for fuel chips varies with local supply and demand across the South but delivered prices of $14-19 per ton are common (Timber Mart South 2006). We project that chips can be produced from limbs and tops (Treatment B) at costs ranging from $11 per ton and up (Figure 2). Also pursuing understory for use in making chips (Treatment C) is approximately $1 per ton more expensive. These per ton costs increase as the volume chipped decreases. We represent this as the ratio of roundwood production to chip production. As this ratio increases, fewer chips are produced. Our estimates suggest that if no more than 10 loads of roundwood are produced before a load of chips is made that this modified system will break even if the market price for fuel chips is $17 per ton. Lower or higher market prices will affect the projected breakeven point.

Table 2. Summary of data collected by treatment and by block.

Treatment	Loads	Tons	Days	SMH	Acres	Tons /load	Tons /day	Tons /acre	Loads /day	Loads/acre	Round Wood Tons/Ac	Chip Tons/Ac	Tons/SMH	Fuel Use Gallon/Ton
A - Conventional Harvest														
Block 3	68	1785	6	52.25	22.63	26.2	297.5	78.9	11	3	78.9	--	34.2	0.4
Block 9	46	1406	7	59.00	23.85	30.6	200.9	59.0	7	2	59.0	--	23.8	0.5
Block 10	43	1279	5	42.50	19.85	29.8	255.9	64.4	9	2	64.4	--	30.1	0.4
Totals	157	4470	18	153.75	66.33	86.6	754.2	202.3	27	7	202.3	--	88.1	1.3
Average	**52**	**1490**	**6**	**51.25**	**22.11**	**28.9**	**251.4**	**67.4**	**9**	**2**	**67.4 Aa**	**--**	**29.4 Aa**	**0.4 Aa**
B -Tops and Limbs														
Block 2	66	1699	8	62.25	23.92	25.7	212.4	71.0	8	3	70.0	1.0	27.3	0.8
Block 4	58	1448	8	60.75	21.93	25.0	180.9	66.0	7	3	62.4	3.7	23.8	0.9
Block 7	60	1637	7	61.00	19.98	27.3	233.9	81.9	9	3	75.3	6.6	26.8	0.8
Totals	184	4784	23	184.00	65.83	78.0	627.2	219.0	24	8	207.7	11.3	78.0	2.5
Average	**61**	**1595**	**7.7**	**61.33**	**21.94**	**26.0**	**209.1**	**73.0**	**8**	**3**	**69.2 Aa**	**3.8 Aa**	**26.0 Aa**	**0.8 Bb**
C - Tops, Limbs, & Understory														
Block 1	63	1698	7	50.50	21.68	26.9	242.5	78.3	9	3	71.1	7.2	33.6	0.9
Block 5	77	2052	10	78.75	25.02	26.6	205.2	82.0	8	3	68.1	13.9	26.1	0.8
Block 8	49	1333	6	42.50	24.63	27.2	222.2	54.1	8	2	42.9	11.3	31.4	0.8
Totals	189	5083	23	171.75	71.33	80.8	669.9	214.4	25	8	182.0	32.4	91.0	2.5
Average	**63**	**1694**	**7.7**	**57.25**	**23.78**	**26.9**	**223.3**	**71.5**	**8**	**3**	**60.7 Aa**	**10.8 Aa**	**30.3 Aa**	**0.8 Bb**

Means with the same letter are not significantly different at the alpha=10% (AB) or 5% (ab) level.

Table 3. Fuel usage per ton by type of woods equipment and study treatment.

Treatment	Feller-buncher	Skidder	Loading	Chipper	Totals
	Gallons/Ton				
A - Conventional logging					
Block 3	0.11	0.15	0.10	--	0.36
Block 9	0.17	0.17	0.12	--	0.47
Block 10	0.15	0.15	0.11	--	0.42
Average	0.15	0.16	0.11	--	0.41 Aa
B – Tops/limbs					
Block 2	0.14	0.18	0.13	0.38	0.83
Block 4	0.15	0.15	0.13	0.46	0.88
Block 7	0.15	0.18	0.14	0.35	0.82
Average	0.15	0.17	0.13	0.40	0.84 Bb
C – Tops/limbs/understory					
Block 1	0.13	0.15	0.13	0.44	0.85
Block 5	0.14	0.15	0.13	0.34	0.76
Block 8	0.15	0.15	0.10	0.45	0.84
Average	0.14	0.15	0.12	0.41	0.82 Bb

Means with the same letter are not significantly different at the alpha=10% (AB) or 5% (ab) level.

Table 4. Properties of chips sampled in the two chipping treatments.

Treatment	MC	C	N	P	K	HHV	
	Percent					MJ/kg	BTU/lb
B –Tops and limbs							
Block 2	46.2	50.4	0.119	0.0148	0.0458	19.6	8015
Block 4	51.9	52.0	0.204	0.0129	0.0412	18.2	8296
Block 7	48.9	51.8	0.211	0.0156	0.0554	19.5	8394
Average	49.0	51.4	0.178	0.0144	0.0475	19.1	8235
C – Tops/limbs/understory							
Block 1	46.8	50.7	0.127	0.0111	0.0311	18.6	8419
Block 5	29.6	50.6	0.304	0.0407	0.1158	19.3	7859
Block 8	49.0	50.8	0.195	0.0135	0.0435	19.5	8381
Average	41.8	50.7	0.209	0.0217	0.0635	19.1	8219

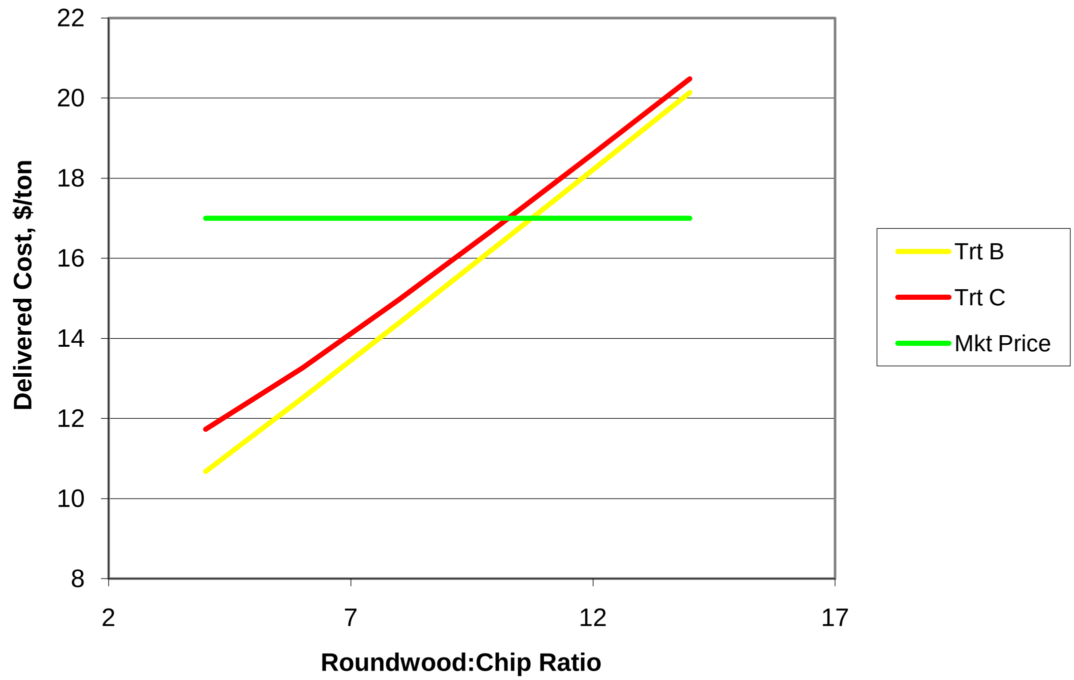

Figure 2. Estimates of delivered chip costs for treatments B (limbs & tops) and C (limb/top/understory) as the number of loads of roundwood required to produce one load of chips varies.

4. CONCLUSIONS

We did not see a significant difference in roundwood production per acre or per hour after adding a chipper to a ground-based tree-length southern pine harvesting operation. Under the right conditions, it appears that a small chipper can be added to obtain additional chip production without adversely impacting roundwood production. Our study involved relatively low volumes of biomass removals (3.8 and 10.8 tons per acre) and the chipper easily handled this volume. Our cost projections suggest that removing only limbs and tops may be marginal in terms of cost as one load of chips was produced for about every 15 loads of roundwood. When small understory stems on the site were also harvested and chipped with the residual limbs and tops, total chip production increased to 10.8 tons per acre or one load of chips for every 5 loads of roundwood. While this approach required additional work from the felling and skidding operation, roundwood production did not suffer significantly and costs appear favorable for this treatment.

The chips produced from these biomass sources worked well in the electricity co-generation plant where they were burned and our lab analyses suggest that the chips also have very competitive heating values. Future work will focus on potential site preparation savings as the sites are raked prior to bedding and replanting. Treatment C sites should require less of this practice due to the higher volume of material removed. We will also monitor the site to see if nutrient issues result from this biomass removal. We also plan to replicate the study on an upper coastal plain site more typical of southeastern forests and to evaluate these chips and those from other sources as a potential feedstock for pyrolysis, gasification, and fermentation processes.

5. ACKNOWLEDGEMENTS

This study was funded by a grant from the Georgia Traditional Industries Program (TIP3) during FY 2006. The cooperation of Langdale Industries and Lott Logging made this study possible.

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Long-term feasibility of timber and forest biomass resources in a mountainous area in Japan*

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Abstract
Forest resource, slope, public and forest road layers of Geographic Information System (GIS) were obtained from a prefecture, where a model area was located, in order to calculate harvesting costs of timber and forest biomass resources. Future forest resources at each stand were predicted using Richard's growth curves. Then, stand harvesting schedules were planned by balancing harvesting volumes of timber and forest biomass resources using random search while minimizing harvesting costs. This schedule will make it possible to supply forest biomass resources to an energy plant stably. The schedule will also be used to supply harvested timbers from the model area stably. Balanced harvesting forest biomass resources will be sufficient to supply electricity to 41.3% of houses in the model area. According to harvesting volumes of forest biomass resources, logging residues and thinned trees were harvested based on the schedule. If the forest biomass resources are not sufficient, broad-leaved forests are harvested to meet sufficient volumes. According to harvesting costs of forest biomass resources, logging residues were the cheapest, 5,000 yen/ton, followed by broad-leaved forests, 11,000 yen/ton; thinned trees were the most costly, 15,000 yen/ton. Then, the optimum scale of a power-generation plant was discussed. With regard to the direct combustion power generation, the optimum scale of a power-generation plant was 3 MW of generation capacity and 18% of energy-conversion efficiency. Its fuel cost of electricity was 10.5 yen/kWh. On the other hand, the optimum scale of a small-scale gasification power plant was 1 MW of generation capacity and 27% of energy-conversion efficiency. Its fuel cost was 4.3 yen/kWh. In order to reduce fuel costs of direct combustion power generation to 10.17 yen/kWh calculated by the average electricity price in Japan, 18.17 yen/kWh, minus the assumed fixed costs of the power-generation, 8 yen/kWh, it is necessary to improve energy-conversion efficiency or to construct forest roads.

1. INTRODUCTION

The Japanese forest industries have been depressed for a long time. There are so many regions where forestry is not mechanized and the logging cost cannot be reduced. On the other hand, forest biomass attracts a great deal of attention in such regions. This is because the energy utilization of forest biomass is expected to contribute to revitalizing the forest industries as well as to maintaining the relevant ecological, economic, and social functions of man-made forests, but many of which are behind in tending. In order to utilize forest biomass as energy in a region

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 435-444.*

where forestry is the major source of income, it is crucial to know the relationship between the annual available amount and the harvesting and transporting cost (procurement cost) of forest biomass in the region. Kuboyama et al. (2004) estimated potential supply using timber production and processing statistics and forest biomass yield tables. Yoshioka and Sakai (2005) have carried out detailed analyses of potential supply based on a geographic information system (GIS). However, these studies have used current status of timber production and processing statistics, forest biomass yield tables, stocks and growth rates in the forests. Nord-Larsen and Talbot (2004) have already assessed long-term availability of forest fuel resources in Denmark.

In this study, long-term feasibility of the energy utilization of forest biomass in a mountainous region in Japan is discussed by analyzing the relationship between the mass and the procurement cost of biomass in the region with the aid of the GIS. A model region was selected, and logging residues, thinned trees, and broad-leaved forests are defined as forest biomass here. Mechanization in forestry for the energy utilization of forest biomass was supposed to be available. To find out the actual situation of the region for the energy utilization of forest biomass, the distribution of forest resources, the topography, and the alignment of forest and public roads were investigated as exactly as possible. Then, growth rates were used to find out the future situation of the region for the energy utilization of forest biomass. Finally, the long-term relationship between the mass and the procurement cost of biomass was discussed while minimizing procurement cost and balancing the mass using random search.

2. MATERIAL AND METHODS

2.1 Study Site

Hikami County in Hyogo Prefecture, the middle part of Japan was selected as a model region here. The gross area of the county is 49,328 ha, the population is 72,862, and the number of households is 21,769. Its climate belongs to the inland and basin type, the annual average temperature is 13-14 degrees Celsius, and the annual precipitation is 1,500-1,600 mm/y. Its forest belongs to the lucidphyllous forest zone, the forest area is 37,202 ha (the percentage to the gross area is 75%), and man-made forest covers 58% of the forest area. The number of sawmills is 43, and the annual consumption of logs for timber is 78,992 m^3/y. Hikami County is a leading region in forestry and timber business in Hyogo Prefecture. However, in the region, the annual cut volume of logs has dropped almost by 50% in the past five years, and the forest stands behind in tending are increasing. Delay in mechanization in forestry is one of the major reasons for such a situation.

2.2 Data

The forest register, the statistics on the forest industries, and the guides to forestry practice were offered from the prefectural office. Using these materials and the GIS, the annual available amount of biomass resources was calculated, and the distribution map was made based on sub-compartments. With regard to the GIS software, TNTmips® (MicroImages, Inc., the U.S.) is used in this study. The shapes and the locations of sub-compartments are vector data, which are managed by the prefecture. The number of sub-compartments in the region was 2,168, and the total growing stock was 7,841,851 m^3. Among these sub-compartments, there were 1,113 man-made coniferous stands and 398 naturally regenerated broad-leaved stands. The DEM of the region (50 m mesh, the Geographical Survey Institute, Japan) is input into the software to calculate the slope of each sub-compartment and to judge the skidding/yarding direction (uphill or downhill). The digital topographic map of the region (1:25,000 scales, the Geographical Survey Institute, Japan) is input into the software, and forest and public roads whose width is greater than 3 m are traced and converted to vector data.

2.3 Procurement costs

Harvesting and transporting systems for forest biomass were classified depending on the parts of a tree for energy and the topographical conditions, and the equations for calculating costs are made. Table 1 lists the operation patterns of sub-compartments to be felled. According to the parts of a tree for energy (logging residues or the whole tree), harvesting and transporting systems for forest biomass are classified into two types (Figure 1). The machine for skidding/yarding is usually decided according to the topographical conditions, i.e., slope, skidding/yarding distance, and skidding/yarding direction (uphill or downhill). In this study, tractors (skidders), tower yarders (mobile yarders), and yarders are to be used for the skidding/yarding process, and Figure 2 shows the classification of skidding/yarding machines according to the topographical conditions of sub-compartments. Table 2 shows the equations for calculating the harvesting and transporting costs of forest biomass whose variables are slope θ (degree), harvesting volumes per ha V (m^3/ha), skidding/yarding distance L_Y (m), and transporting distance L_T (m). The costs of labor, machine, and fuel are considered here.

Finally, the following items on topography are processed on the GIS software. The average angle of inclination of each sub-compartment is calculated. To determine skidding/yarding distance of each sub-compartment, the distance between the center of gravity of a sub-compartment and the nearest road from the sub-compartment is calculated. A landing is to be arranged at the point on the nearest road from the sub-compartment. The skidding/yarding direction (uphill or downhill) is judged by comparing the altitudes of the center of gravity with the landing. Transporting distance from landings to energy-conversion plant is calculated by the shortest path function of GIS software. By applying the topographical data on each sub-compartment to the equations listed in Table 2, the procurement costs of forest biomass from all sub-compartments in the region can be calculated.

2.4 Energy-conversion plant

Two types of an energy-conversion are considered in this study. One is a direct combustion and another is small-scale gasification. Two types of plant location are also considered in this study. One is a central system and another is a distributed system. A central system means that a direct combustion plant or a small-scale gasification plant is assumed to be located on No.2 (Figure 3). On the other hand, a distributed system indicated that six small-scale gasification plants are assumed to be located on No. 1 to No.6. Yagi and Nakata (2006) reported the energy-conversion efficiency of direct combustion and small-scale gasification is expressed by the following equations (Figure 4):

Direct combustion power-generation: 5.35xLN(generation capacity kW)-24.59 (1)
Small-scale gasification power-generation: 3.14xLN(generation capacity kW)+5.10 (2)

Figure 5 shows the relationship between generation capacity and harvesting volumes.

2.5 Available amount of forest biomass

The total stem volume of each sub-compartment is recorded in the forest register. Therefore, if the coefficient that converts stem volume to dry mass is known, the amount of biomass resources can be calculated from the stem volume and the coefficient. The coefficients to calculate the amount of biomass resources are listed in Table 3. Consequently, by applying Tables 1 and 3 to the forest register and considering the cutting cycles of coniferous and broad-leaved forests, the annual available amount of forest biomass in the region can be calculated. To find out the future available amount of forest biomass V (m^3/ha), Richard's growth curves with the year t are applied to the forest register:

Conifer: $V=377(1-\exp(-0.047t))^{2.26}$ (3)

Broad-leaves: $V=281(1-\exp(0.032t))^{1.82}$ (4)

2.6 Balancing harvesting volumes of timber and forest biomass resources

In order for energy-conversion plant to work stably, forest biomass resources should be provided to the plant stably. In this study, stand harvesting schedules were planned by balancing harvesting volumes of timber and forest biomass resources using random search while minimizing harvesting costs.

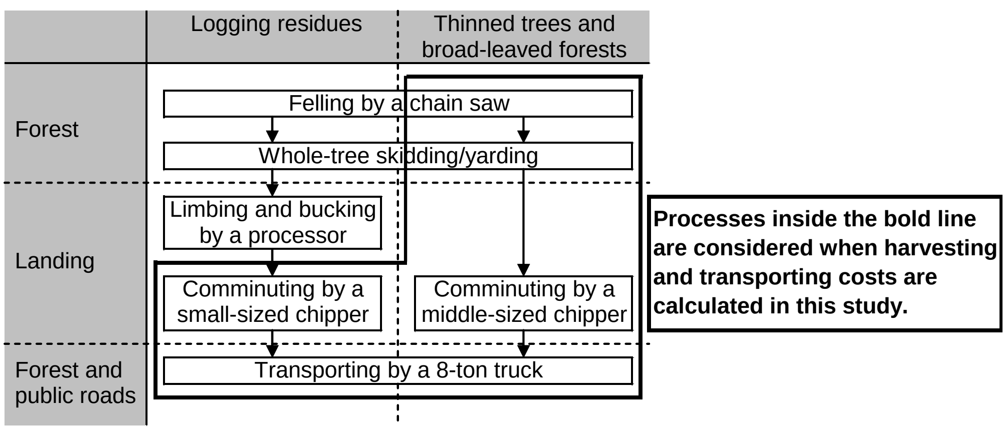

Figure 1. Classification of systems according to the parts of a tree for energy

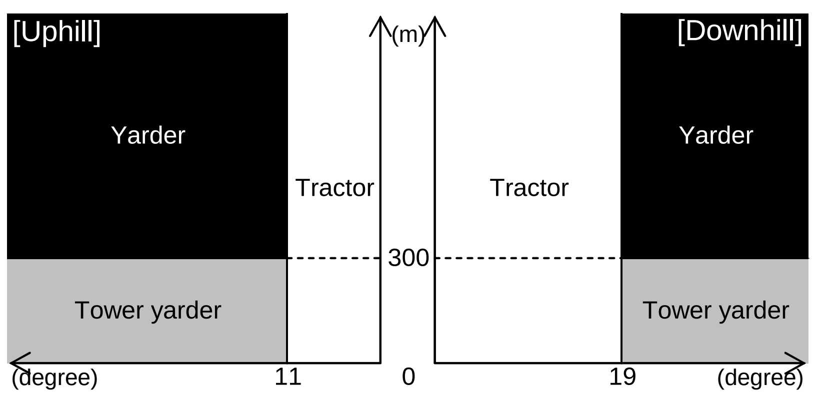

Figure 2. Classification of machines according to the topographical conditions

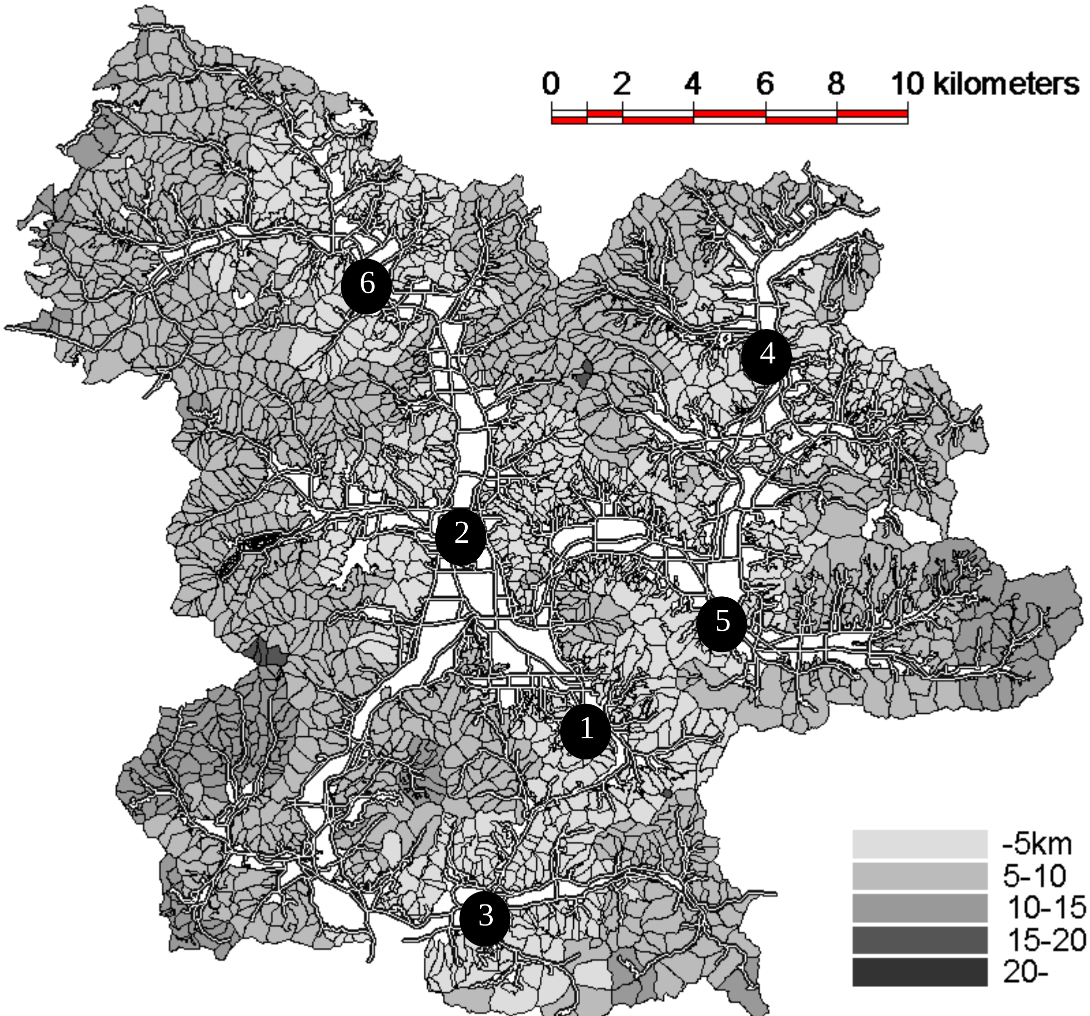

Figure 3. Transporting distance to energy-conversion plants (A direct combustion power plant or a small-scale gasification plant is located on No.2 in the central system and six small-scale gasification plants are located on No.1 to No. 6 in the distributed system)

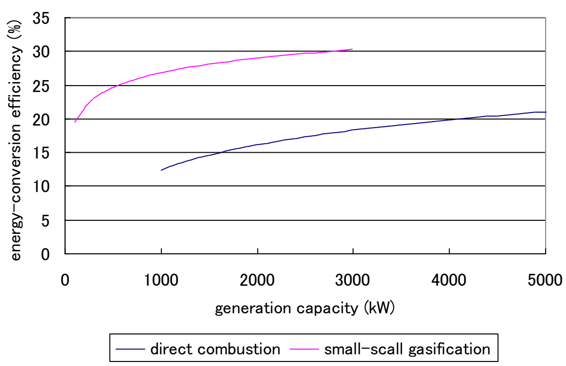

Figure 4. generation capacity and energy-conversion efficiency

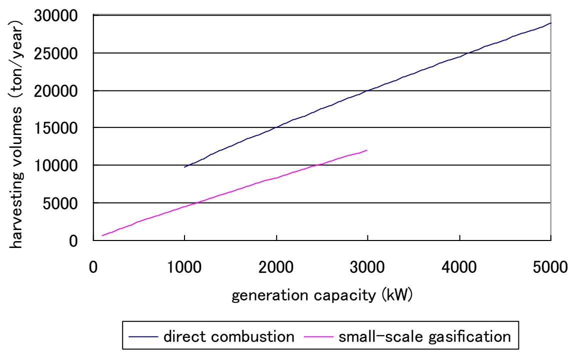

Figure 5. generation capacity and harvesting volumes.

Table 1. Operation patterns of sub-compartments to be felled

Forest	Age (y)	Operation pattern
Man-made and coniferous[1]	31-60	[Biomass resources: Thinned trees] Thinning is carried out in the stands of which stocks are more than Richard's growth curves with a 20% or more thinning rate so that stocks are below Richard's growth curves, and the whole trees are used as energy sources.[2]
	Over 61	[Biomass resources: Logging residues] Clearcutting is carried out to all the stands. Trees are limbed and bucked, logs are harvested, and tops and branches are used as energy sources.
Naturally regenerated and broad-leaved[1]	Over 31	[Biomass resources: Broad-leaved forests] Clearcutting is carried out at 30-year interval cycle, and the whole trees are used as energy sources.

[1]The representative tree species in the region are "hinoki" or a cypress (Chamaecyparis obtusa) for coniferous and "keyaki" or a zelkova (Zelkova serrata) for broad-leaved.
[2]It is supposed in this study that all of the cut material at thinnings can be used as an energy source in consideration of the actual Japanese market value.

Table 2. Procurement cost (yen/m^3)

Machine	Remark	Cost
Chain saw	Conifer	1,000
	Broadleaf	1,125
Tractor	Whole tree	$0.845L_Y+27{,}510e^{0.117\theta}/V+1{,}746$
Tower yarder	Whole tree	$5.540L_Y+4{,}308{,}900/L_YV+643$
Yarder	Whole tree	$761.592/L_Y^{-0.2142}+3{,}722{,}700/L_YV+118{,}200/V+196$
Processor	Whole tree	1,954
Chipper		1,039
Truck	Cut-to-length	$0.022L_T+778$
	Chip	$0.027L_T+778$

Table 3. Methods for calculating the amount of biomass resources

Biomass resources	Equation (s.v.: Stem volume)	Note
Logging residues[1]	Amount (tDM) = s.v. · 15/92 · 0.40	· 15/92: Ratio of tops and branches' volume to stem volume · 0.40: Density of a coniferous tree
Thinned trees	Amount (tDM) = s.v. · 20/100 · 100/92 · 0.40	· 20/100: Thinning rate · 100/92: Ratio of the whole tree's volume to stem volume · 0.40: Density of a coniferous tree
Broad-leaved forests	Amount (tDM) = s.v. · 100/80 · 0.56	· 100/80: Ratio of the whole tree's volume to stem volume · 0.56: Density of a broad-leaved tree

[1]The method for calculating the cut volume of logs in clearcutting is as follows:
Volume of logs (m^3) = s.v. · 85/92 (85/92: Ratio of logs' volume to stem volume)

3. RESULTS

The maximum available amount of forest biomass is 30,106 ton/year with which about 5MW direct combustion power plant works (Figure 5). This plant will be sufficient to supply electricity to 41.3% of houses in the model area. According to harvesting volumes of forest biomass resources, logging residues and thinned trees were harvested based on the schedule. If the forest biomass resources are not sufficient, broad-leaved forests are harvested to meet sufficient volumes (Figure 6). According to harvesting costs of forest biomass resources, logging residues were the cheapest, 5,000 yen/ton, followed by broad-leaved forests, 11,000 yen/ton; thinned trees were the most costly, 15,000 yen/ton. As target volume of forest biomass decrease, harvesting costs of forest biomass resources decrease as well due to the reduction of harvesting volumes of thinned trees and broad-leaved trees of which harvesting costs are high (Figure 7).

Then, the optimum scale of a power-generation plant was discussed on the model area using Figure 5 and Figure 7 on a direct combustion power plant and a small-scale gasification power plant. With regard to the direct combustion power generation, the optimum scale of a power-generation plant was 3 MW of generation capacity and 18% of energy-conversion efficiency (Figure 8). Its fuel cost of electricity was 10.5 yen/kWh. On the other hand, the optimum scale of a small-scale gasification power plant was 1 MW of generation capacity and 27% of energy-conversion efficiency. Its fuel cost was 4.3 yen/kWh. In the distributed system, the optimum scale of six small scale gasification power plants was 0.1 MW of generation capacity and 20% of energy-conversion efficiency. Its fuel cost was 6 yen/kWh. When the limit of fuel costs is assumed to be 10.17 yen/kWh calculated by the average electricity price in Japan, 18.17 yen/kWh, minus the assumed fixed costs of the power-generation, 8 yen/kWh, it is important to use the small-scale gasification power-generation for energy utilizations of forest biomass resources.

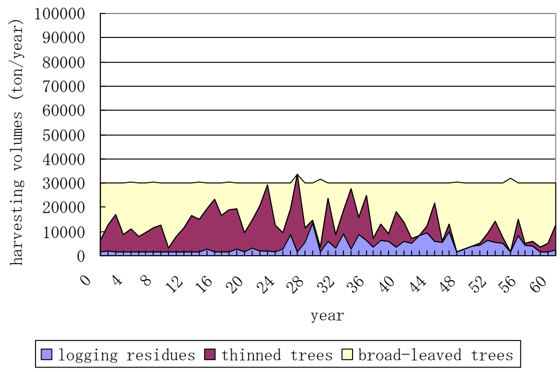

Figure 6. harvesting volumes.

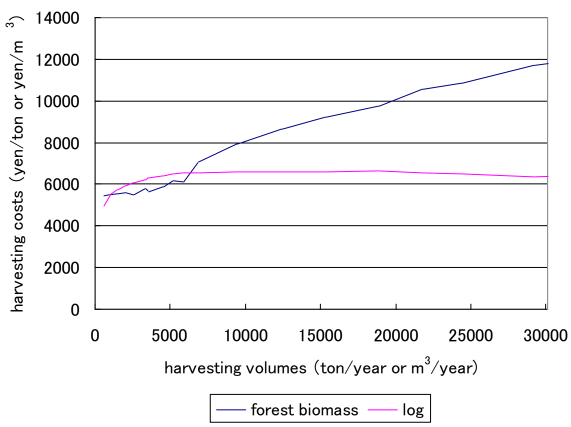

Figure 7. harvesting volumes and costs.

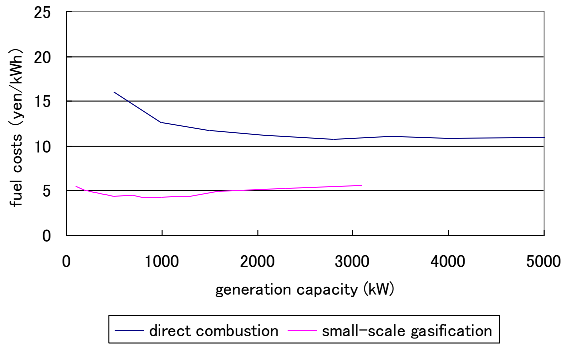

Figure 8. fuel costs in the central system

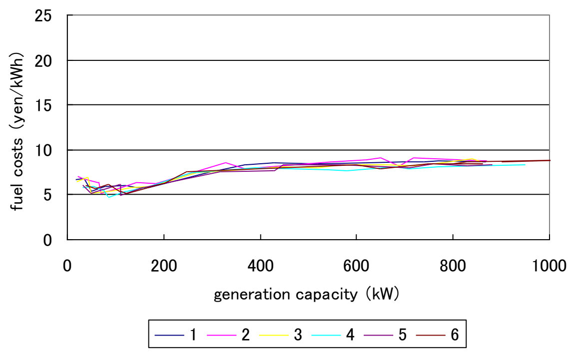

Figure 9. fuel cost in the distributed system

4. DISCUSSIONS

In order to reduce fuel costs of direct combustion power generation to 10.17 yen/kWh, it is necessary to reduce harvesting costs remarkably by developing forest road network and machines for harvesting and transporting forest biomass resources efficiently. In this study, the effect of forest road construction on harvesting costs is discussed. Forest roads are assumed to be constructed so that skidding/yarding distances were reduced by 100m, 200m, or 300m each skidding/yarding operation constantly. As a result, forest road construction reduced fuel costs of electricity from 10.5 yen/kWh to 7.2 yen/kWh (Figure 10). Total cost including the cost of harvesting and forest road construction was also reduced (Figure 11). Therefore, it is important to reduce fuel costs remarkably by developing forest road networks.

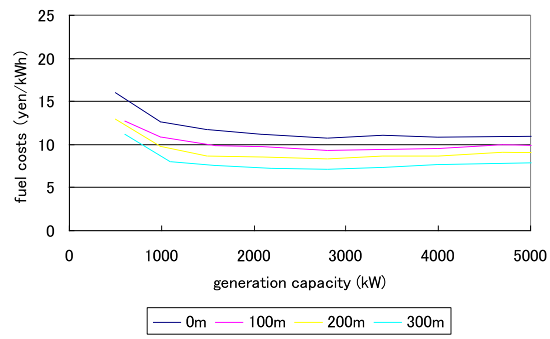

Figure 10. Fuel costs after forest road construction.

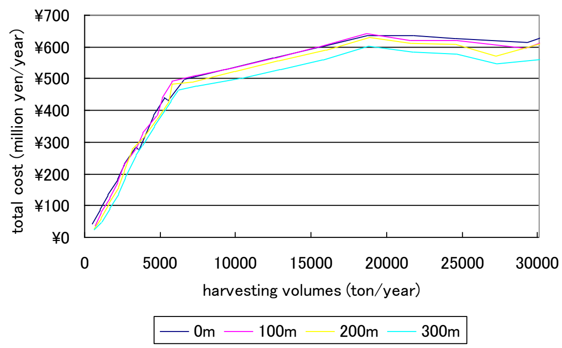

Figure 11. Total costs.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Survey of forest fuel Reduction managers*

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Abstract
Because of the resurging problem with wildfires, foresters and other land managers in nearly every state have begun forest operations wherein fuel reduction is a primary management objective. Literature on this wave of activity, begun mostly since 2000, is just now becoming common. To obtain a better concept of the extent and nature of forest fuel reduction activities in the nation, a survey of foresters and similar administrators was conducted. The analysis resulted in classifying mechanical and burn only operations based on the nature of projects

1. INTRODUCTION

Because of the resurging problem with wildfires, foresters and other land managers in nearly every state have begun forest operations wherein fuel reduction is a primary management objective. Literature on this wave of activity, begun mostly since 2000, is just now becoming common. To obtain a better concept of the extent and nature of forest fuel reduction activities in the nation, a survey of foresters and similar administrators was conducted.

Through the results of the survey, it was anticipated that a better overview of the topic can be obtained. Currently, there are several reports on specific fuel reduction projects (Hungry Creek Project, Brown Darby Fuel Reduction Project, Applegate Fire Plan Project and others) and summary publications on commercial mechanical equipment available for fuel reduction activities (Windell and Bradshaw 2000; Ryans and Cormier 1994). There is a need for a publication that provides an overview of the localities, types and effects of recent and current fuel reduction activities. Such a publication will increase the general knowledge about fuel reduction projects, provide a basis for mutual contacts, and reduce duplication of effort.

2. FUEL REDUCTION SURVEY

A survey of Forest Administrators/Fire Chiefs and other administrators who would probably over see fuel reduction projects was conducted in 2004. For each state, information was gathered to determine the best contacts for forest fuel reduction projects. The information was gathered through web sites, email, and through direct telephone contact. All persons contacted were employees of public agencies, especially the U.S. Forest Service and the state forestry agencies. Over 600 individuals were contacted.

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 445-451.*

Questionnaire: The questions were designed to address a fuel reduction project which had been completed lately or was in progress. Some questions asked about the project details such as the area treated, topography, type of machines used, and cost or revenue to treat an acre. Other questions were of a more general nature, such as fuel reduction awareness among communities and local citizens' actions. Contact information of the respondent was asked, but the information may be made available only if the respondent agrees to it. The last section of questionnaire addresses the demographics of the respondent; this information will be useful in the future in assessing demographic changes in the profession.

Verification of the Questionnaire: The questionnaire was reviewed by several personnel knowledgeable in this particular field, and changes were made accordingly. The first questionnaires were sent to a random sample of thirty addressees. They were asked to critique the questionnaires. Changes were made accordingly before the other addressees were contacted, but the changes were very minor.

Mailing: Post cards were mailed to the addressees to create awareness of the survey and its importance. A week later the survey was mailed to them. A reminder post card was mailed one week later. A second mailing was done after 3 weeks to the non-respondents. There is a body of literature that suggests that people who do not respond to survey have characteristics similar to those who respond to second mailing. Responses to the two mailings were kept segregated.

3. SURVEY RESULTS

Approximately 197 people responded to the survey out of the 681 mails outs. Responses to first mail out were 20 % and to the second mail out was 12%, the net response rate being 31 %. Respondents were 84% male and 16% females with age range 25-66. Among these about 20% had some college education, 57% were college graduates and 17% had graduate degrees. Their primary occupations were District Rangers, FMO, Foresters and Firefighters. Among the respondents, about 65% were employed with the USDA, 18% were with US BLM and the remaining 14% were with state forestry agencies. The results from the respondents were classified in to two groups the first being mechanical fuel reduction projects, where machinery were used to carry out the complete operation, the other was classified as prescribed burn projects only, where the entire fuel reduction was carried out with a controlled burn .

Mechanical Operations:

Approximately 151 projects were categorized as mechanical operations, as they used techniques such as hand piling, forestry mulchers or logging equipments followed by a burn. The majority of the projects were carried out on government owned lands which were in the wildland-urban interface area. The topography for the majority of the projects was moderate, which had a gradient between 10-35 %. Fig. 1 indicates the fuel conditions based on the projects, heavy ladder fuel and dense small dia conifer stands dominate the conditions in the bar chart. The number of acres for these projects ranged from a minimum of 5 acres/project to a max of 12,325 acres/project. The projected time for completion ranged from a single day to 2,555 days using a mean of 5.5 (SD =8.3) administrative personnel and a mean of 21.6(SD=31) operational personnel.

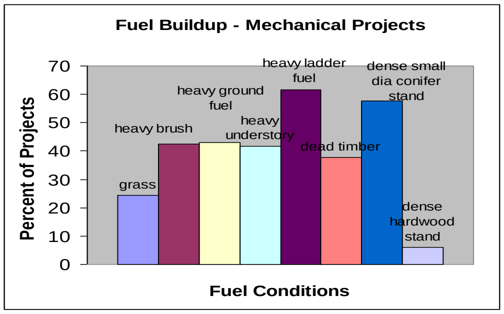

Figure 1

Cost /revenue:

Responses indicated that some projects were carried out based on the funds from grants by USFS and other agencies. Some projects cost and revenue went to the government. Other projects indicated the use of firewood to landowners. In general, the cost to land owner was $ 390 (SD=574) and the revenue to the land owner was $ 108 (SD=350). Also majority of the projects had some of the products marketed for logs, paper chips and landscape mulch (Fig 2)

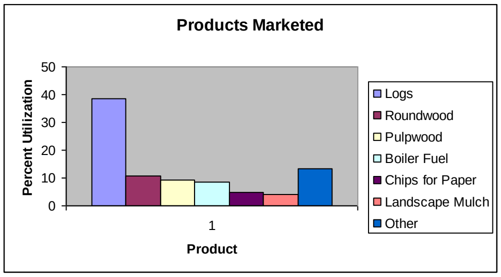

Figure 2

Fuel Reduction Machinery:

Chain saws, skidders, in-woods chippers and feller bunchers were among the popular machinery (Fig 3). The machines classified under category other were dozers, skyline cable yarders and helicopters.

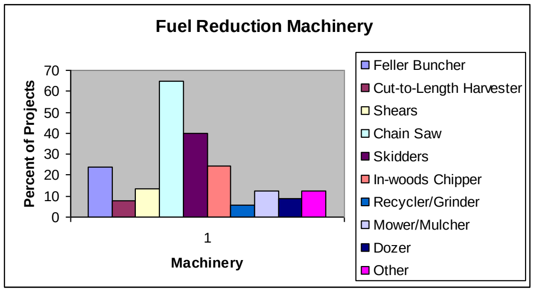

Figure 3

Time before pretreatment:

To get a concept of the perceived effectiveness of the fuel reduction treatments, we asked the respondents to estimate the amount of time until the treatment will need to be repeated. Majority of the projects carried out were estimated that it would take more than 7 years to do the same kind of fuel reduction work carried out. A few projects were classified to take about 2-7 years and less than 5% required no treatment at all.

Problems associated with operations:

Administrative, cost finding market for the materials were the top three problems which were ranked high based on the projects. Weather conditions also play an important role for any given project as illustrated (Fig 4). Some of the common problems found under the category other were related to computer problems, social acceptance, social values, limited work force, NEPA, contractors who did not assess the area's before bidding, land owner concerns, litigations environmental concerns and no funds after the site was treated.

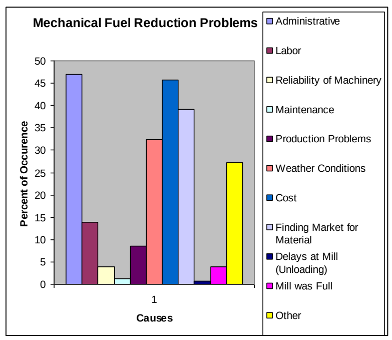

Figure 4

Burn only operations:

About 46 projects were categorized as burn only operations where prescribed burn was the major operation carried out to reduce the fuel build up.

The majority of the projects were carried out on government owned lands which were in the wildland-urban interface area. The topography for the majority of the projects was moderate, which had a gradient of 10-35 %. Fig 5 indicates the fuel conditions based on the projects, heavy ground fuel conditions with grass and heavy brush dominate the conditions in the bar chart. The number of acres for these projects ranged from a minimum of 5 acres/project to a max of 46000 acres/project. The projected time for completion ranged from a single day to 62 days with a mean of 4.13 administrative personnel and a mean of 22.95 operational personnel.

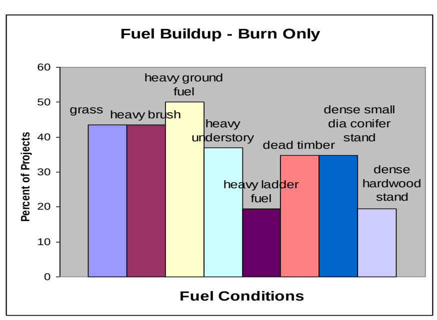

Figure 5

Cost:

The cost to run the burn operation per acre had a mean of $ 104.86 with min and max ranging from 0 to 1000 dollars per acre. 5 % reported a cost of $ 0 per acre, but no information was available whether a project was carried out free of cost to the land owner or whether some of the projects were actually funded by other agencies.

Prescribed Burn Machinery:

Chain saws were used in majority of the projects and the common equipments listed under the category other were helicopters. drip torches, trucks, ATV's and dozers.

Time before retreatment:

Majority of the projects did require to be treated again based on the geographic locations, the time frame (Fig 6) varied from 2 – 7 years before any kind of treatment was necessary. A few projects which accounted for less than 5 % required no treatment at all.

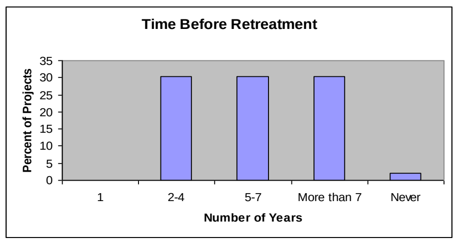

Figure 6

Problems associated with operations:

Weather conditions seemed to play a very important role which had a major effect on almost 70 % of the projects and the remaining dominating categories were due to administrative and other to name a few. Common problems under category "other" were due to smoke management, politics, funding, public understanding, tourist trade impacted and NEPA.

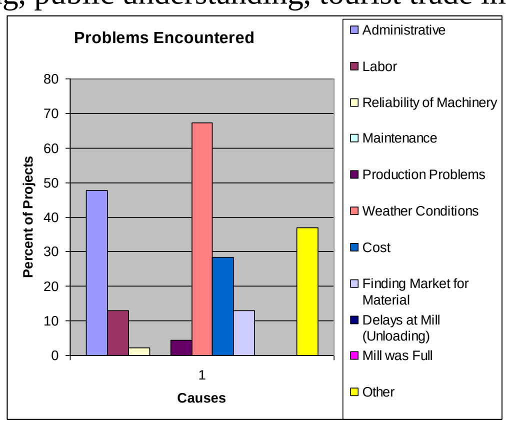

Figure 7

Combined Analysis:

This section of the survey was to seek answers to general questions whether the project was through mechanical operation or prescribed burn only operation. Typical questions included if projects can be carried out with available equipment or if there was a need to design a totally new machine, 72 % of the respondents felt that projects can be carried out with existing machines and some of the existing machines can be modified to suit the conditions. A few respondents felt newer designs were necessary as conventional machinery could not be really used in steep slopes, compact chippers which can be cabled to the work site were necessary at very steep conditions and compact machines that can keep tree spacing with out damaging them.

Educational awareness among citizens and their active involvement in fuel reduction programs play a significant role in any given situation. A few questions were targeted on awareness programs available to citizens, steps they can take to contribute to fuel reduction programs with a probable use of existing agricultural machines than investing on special machinery.

Approximately 59 % of the respondents indicated that there were educational programs, including, Firewise Programs, Firesafe council, awareness programs promoted through schools and public meetings. 55% indicated that there was substantial citizen involvement on fuel reduction projects, much of those were from land owners adjacent to forest lands.

A few comments from the forest administrators to citizens stressed on the importance of landowners to take the initiative and create defensible space around their homes and property. Possible grants through the Firewise and Fire Safe programs to execute fuel reduction around their homes and community and the advantages of state sponsored programs. Ask local firefighters or forest service personnel about what can be done to protect their homes.

About 32 % indicated that there was reluctance on the part of landowners to allow fuel reduction machinery on their property. Some comments included that they didn't want trees cut or land disturbed because of invasion of privacy, damage to residual vegetation, effects on wildlife, dust and erosion.

Approximately 33 % of the respondents had come across reports relating to fuel reduction and the most common were from National Fire Plan Operations Reporting System, NFPORS (www.NFPORS.gov), Forest Service Fuel Reduction Reports and National Fire Plan website. (NFP)

4. DISCUSSION

Although the intention of this survey was to describe mechanical fuel reduction operations, many of the respondents described fuel reduction operations wherein only prescribed burning was conducted. A comparison of the two types of operations turned out to be interesting.

A comparison of the types of fuel reduction operations by fuel buildup type revealed that the mechanical operations (Fig 1) tended to be used more where there are conditions of heavy ladder fuels and dense small-diameter conifer stands. By contrast, burn-only operations (Fig 5) tended to be used more commonly where grass and heavy ground fuels were common.

The mechanical and burn-only operations contrasted dramatically in size. Burn-only operations were three times larger, and yet they were performed in a small fraction of the time (Table 1).

Table 1

	Mechanical		Burn-Only	
	Acres	Days	Acres	Days
Mean	1,396	248	3,180	12
Min	5	1	5	1
Max	12,325	2,555	46,000	62

While mechanical operations often had a revenue stream to offset costs to landowner, the revenues were not sufficient to overcome the costs (on average Table 2). Most of the really costly mechanical operations (over $1,000 per acre) had very little offsetting revenues (often less than $100 per acre).

Table 2

	Mechanical		Burn-Only	
	Revenue	Cost	Revenue	Cost
Mean	$108 (n=28)	$390 (n=100)		$105 (n=36)
Min	0 (n=101)	0 (n=48)		0 (n=9)
Max	$3,000	$4,000		$1,000

5. CONCLUSIONS

This survey represents an over view of the important factors involved in carrying out a mechanical operations and burn only operations based on the type of operation which is necessary. A comparison between any mechanical operations or any burn only operations is difficult as projects are unique based on the fuel conditions, topography, man power , machinery used , funds available etc…Based on the responses it was decided to separate mechanical reductions and burn only operations to better understand these operations.

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Wood Supply Chain Efficiency and Fiber Cost: What Can We Do Better?*

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Abstract
Fiber is the largest component of cash manufacturing costs. As such, fiber availability and cost have large impacts on industrial profitability. We begin with the examination of wood supply chains across the world's major wood producing regions, including the U.S. South, Western Canada, Brazil, Sweden, and Australia. We evaluate the effectiveness of particular systems based on information about their structure, stumpage costs, and delivered wood costs. Using the linerboard sector as an example, we also examine the impact of using virgin fiber vs. recycled fiber on manufacturing costs. These regional comparisons are used to identify strategies that should be considered by the industry in the U.S. South for improving wood supply chain efficiency. A special emphasis is placed on what wood processing mills can do to improve the wood supply chain efficiency, both in terms of reducing costs and improving fiber availability, including policies associated with truck weight limits, scheduling, equipment, and contracting.

1. OBJECTIVES AND METHODS

the forest products industry in the U.S. faces increased competition from every corner of the globe. In addition, population pressures and changes in land use in the U.S. South where the industry has traditionally been most competitive are also impacting the industry. For years the industry was a low-cost producer, benefiting from excellent infrastructure, productive forests on low-cost land, innovative logging contractors, and strong product markets. The U.S. South is no longer the lowest cost producer, however, even after discounting the impact of the recent weak dollar (RISI 2004). Recent research supported by the Wood Supply Research Institute identified that unused logging capacity alone cost the wood supply chain nearly $400 million per year or about $2 per ton (Greene et al. 2004).

Fiber is the largest component of cash manufacturing costs in forest industries. As such, fiber availability and cost can have a substantial impact on industrial profitability. To successfully compete in a global marketplace, our industry must continually evaluate how it supplies its mills and implements changes to keep it competitive. To address these questions, we assess: (1) the cost of doing business in the U.S. wood supply chain compared to foreign competitors, and (2) how the wood supply chain can be modified to improve its competitiveness in world markets. The major wood producing regions examined include the U.S. South, Western Canada, Brazil, Sweden and Australia. We evaluate the effectiveness of particular systems based on information about their structure, stumpage costs, and delivered wood costs. The delivery process includes procuring, harvesting, and transporting fiber to the production facility's woodyard and processing there. These regional comparisons are used to identify strategies that

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 455-461.*

should be considered by the industry in the U.S. South for improving wood supply chain efficiency.

2. RESULTS

In terms of delivered pulpwood prices, the U.S. South is generally competitive with the rest of the world (Figure 1). Delivered softwood prices tend to be higher in Sweden, Western Canada, and Australia. The prices are lower in Brazil, but this gap has been narrowing recently. After accounting for operational conditions, the U.S. South also seems to be competitive on a global scale.

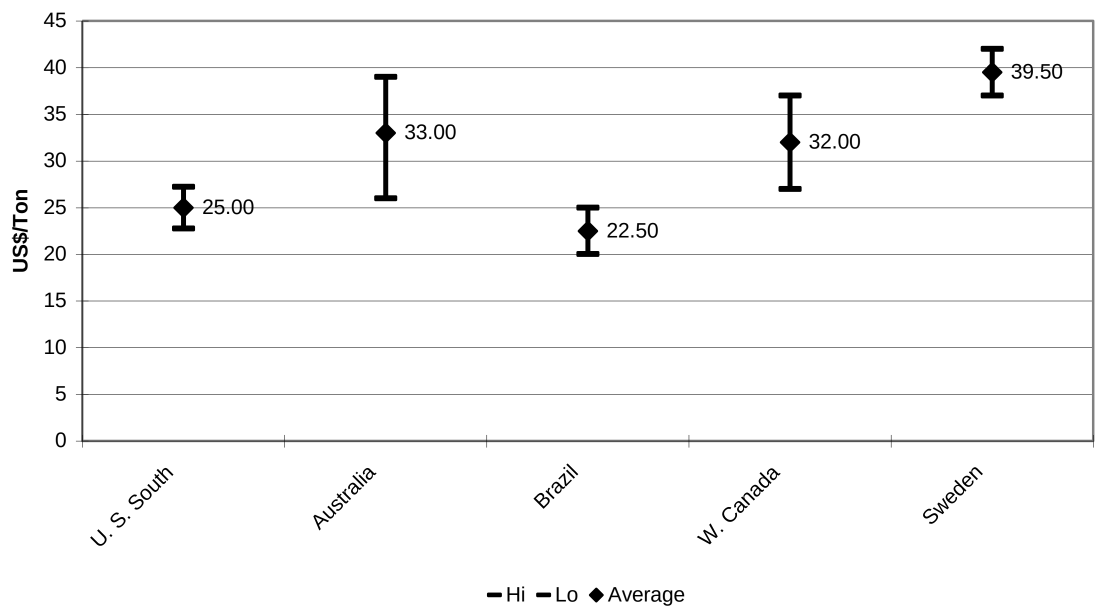

Figure 1. Delivered softwood pulpwood prices, 2005.

Brazil has the lowest wood delivery costs, largely because the wood comes from uniform plantations located close to the mill (Table 1). Furthermore, we find that comparative advantage and the competitive positions of the regions studied have become more changeable and temporal, indicating that global competition is increasingly intense. Exchange rate changes are responsible for a large part of the short-term change. Next come labor costs including benefits that frequently are the deciding factor in a region's ranking.

Table 1. Logging cost estimates, 4th quarter 2005.

	US South	Australia	Brazil	W Canada	Sweden
	$US/green short ton				
Harvesting/Extraction/Loading	11 - 13	6 - 18	5 - 7	9 - 12	10 – 17
Hauling Rate	4 - 11	4 - 9	2 - 4	9 - 13	4 - 8
Total Cut-n-Haul	15 - 24	10 - 27	7 - 11	18 - 25	14 - 25

Major operational differences between the U.S. South and other major wood supply regions include truck payloads, scheduling and dispatching, contract hauling, cooperative maintenance, and logging contracts. Our competitors operate primarily in the “cut-to-length” system. Trucking in the major competing regions employs larger payloads than that allowed by gross vehicle limits in the U.S. South. Truck payloads reach 55 tons in Brazil on public roads, and as much as 66 tons on private roads. This is more than twice as much as currently allowed in the U.S. South (25-29 tons). On-board scales are uniformly used in Australia to ensure maximum payloads. Our competitors have also better scheduling and dispatching systems that allow eliminating much of truck wait time while loading and unloading. This, in part, is a result of a different approach to wood hauling, which is based on trucking contractors independent from wood harvesting operators. Further, multi-shifting of all logging operations in Brazil and beyond is also common. The enterprises operate the best machinery available, maintain it well, and operate the machinery up to 20,000 h before retiring. Finally, our competitors benefit from longer work contracts that can be used for financing their operations. Last but not least, our competitors devote substantial resources to research, training, safety, and environmental compliance. At least some of these factors should be considered by the southern industry in evaluating approaches to improve their competitive standing.

Further, our competitors benefit from the fact that forest management, logging, and wood manufacturing operations are closely integrated either through ownership or contracts. Integration and the resulting larger scale of operations allows for a number of efficiency gains in planning and scheduling, in addition to other advantages associated with scale economies. In contrast, the U.S. South appears to be heading in the opposite direction.

To assess the prospective efficiency gains of fully loading our trucks more consistently, we analyzed 24 southern mills. The study found that ensuring maximum payloads and reducing load variability positively affects the wood supply system. In essence, more wood is transported in fewer trips. The resulting savings range from 4 to 13 percent, meaning that the southern wood supply system could save as much as $100 million annually (Hamsley, et al. 2006).

We further evaluated the impact on trucking costs associated with higher payloads in the U.S. South by increasing the gross vehicle weight from 40 to 48 tons, as most highways are constructed to accommodate the increased weights. The potential cost savings reach 18 percent. The combined savings of fully loading trucks more consistently and implementing higher payloads could range from 20 to 30 percent.

3. DISCUSSION

The results indicate that the southern industry should consider at least some of the approaches implemented by our competitors to improve its own competitive standing. Clearly, the use of on-board scales to ensure full truck loading and higher payloads has the potential to reduce logging costs in the U.S. South. Some of these changes can be made by individual loggers, encouraged by the mill, while others need state level changes (e.g., a weight law). The mill can play an important role in this process, that of an integrator. Unlike our competitors, our industry is very much disaggregated which makes planning and change implementation a much more challenging task. The mill can and should encourage changes by developing wood delivery policies that encourage full, consistent loading and truck scheduling to minimize down time. This would reduce the number of trucks on the road, yielding numerous benefits to all wood supply chain participants as well as the general public using the same roadways.

Further, we need to recognize that wood supply chain efficiency needs to be studied through to the final product. The U.S. pulp and paper industry is being challenged by competitors, who despite having higher delivered wood costs, are fiercely competitive on the final product basis. This occurs in linerboard production, which is particularly important in the U.S. South. Competitors achieve these results by operating modern machinery, using innovative fiber strategies which include the increased used of recycled fiber, and developing new or modifying existing products (e.g., lighter linerboard grades).

The problem is that U.S. paper mills as a group are no longer world-class (Siry et al. 2005). Paper machines in the U.S. South are by far the largest in the world, reaching capacities of 450 thousand tons on average. They are also old—their technical age is about 21 years. Overall, southern machines are average in terms of asset quality, which in turn suggests that these machines are expensive to operate.

Machines in the U.S. South have fairly high production costs approaching $270 per ton. It should be noted here that the new machines put into operation across the world are likely the lowest cost producers. As modern capacity grows elsewhere, cost pressures on the southern industry will continue to mount. Wood and personnel costs were the major cost drivers in the U.S. South, while Latin America has the cheapest fiber and personnel. While wood prices in the U.S. South have already receded from 2003 levels, personnel costs are likely to remain high. As the machines continue to age, they will continue to lose competitive position.

The U.S. industry's position is further eroded by changing markets for packaging materials, primarily by the development and widespread use of cheaper alternatives to kraft linerboard by foreign competitors. About two thirds of European capacity is based on recycled fiber, and Asia produces large volumes of kraft-top testliner. Southern kraft linerboard, while a superior quality product based on virgin fiber, is not cost competitive in some applications. Cheaper alternatives appear to do an acceptable job elsewhere, shrinking our market share.

While the consumption of the recycled fiber has grown over time, the U.S. industry should reconsider the strategic use of recycled fiber, primarily of old corrugated containers (OCC), in the production of linerboard. Recycled linerboard mills represent only 11 percent of the southern linerboard capacity. Our kraft mills also use limited volumes of recycled fiber (normally up to 20 percent). In total, recycled fiber accounts for about a quarter of the linerboard output. While the United States does use recycled fiber, it may have misjudged the competition and does not sufficiently employ a combined product strategy. Our competitors produce and utilize large volumes of cheaper testliner, oftentimes manufactured in smaller and cleaner mills that can be located closer to recycled fiber supplies. In places were kraft linerboard is called for, our competitors commonly use lighter linerboard grades, which are cheaper to produce.

Therefore, while our logging industry certainly can do and should do several things to bring wood costs down, it needs to be recognized that the industry is already fairly competitive and doing a relatively good job, given the operating conditions. This implies that the true competitive position needs to be studied at the final product level as well as the wood cost level.

4. CONCLUSIONS AND RECOMMENDATIONS

Comparative advantages of wood producing regions are not static – they change over both the short and long-term. This suggests that the competitive positions of the regions should be monitored on an on-going basis. Global competition is increasingly intense. Exchange rate changes are responsible for a large part of the short-term change.

4.1 Wood Sources and Cost

- Wood cost rankings by region can change frequently and cost ranges often overlap.
- Currency exchange rates are often the key factor affecting the cost ranking of regions.
- Our true competitive position needs to be studied at the final product level as well as the wood cost level. Other recent studies indicate that US paper mills as a group are no longer world-class, thus other regions are more competitive on a final product basis even though the US South is competitive at the raw material level.
- Stumpage costs are established by mechanisms other than a free market in some of the studied regions. The US South and Sweden rely heavily on open-market purchases from private landowners. Brazil relies nearly exclusively on wood from plantations of exotic species, often owned by the same company that owns the mills. Western Canada mills rely on Crown timber but pay for silviculture, regeneration, and extensive road building costs.
- Logging contractors in many other regions work under longer-term contracts (1-3 years) than typically seen in the US South. This facilitates greater autonomy on the part of the contractors and allows them greater leverage in negotiating capital financing and other business arrangements to strengthen their business.
- Labor costs (including benefits) frequently are the deciding factor in a region's ranking. The gap between labor costs in Brazil and the other four countries is not as large as is often cited when all labor costs are considered. However, Brazil clearly enjoys a labor cost advantage.
- Cost of environmental compliance (from forest to mill) appears to be fairly comparable in the five regions we examined due to a combination of government regulation and widespread third-party certification of industrial forests. It should be noted that other countries not in this study have significant issues with illegal logging and with environmental non-compliance. (Russia, almost all of Asia, etc.)
- The South is increasingly operating as a non-integrated free market wood economy. Other regions are more integrated and concentrated. Does this put the free-market US South at a disadvantage?

4.2 Trucking & Logistics

- Trucking in our competing countries employs larger payloads (up to 100% larger) than that allowed by gross vehicle weight limits in the US. This permits cost-effective trucking over longer distances or provides a significantly lower trucking cost at comparable distances to those seen in the US.

- Truck weights are much more tightly controlled and monitored in other countries with stiff fines beginning when weights exceed limits by as little as 2-5%. Many US states permit 5-10% weight tolerances.
- Loaded truck weights in the US are highly variable causing both significant underloading and overloading of trucks. A minority of US log trucks are weighed before leaving the woods while in many other countries the majority of trucks are weighed, thus permitting greater control of payload.
- Our research indicates that greater control of truck loading (less variable weights) leads to greater payloads. This is an opportunity that can be exploited without regulatory changes and regardless of what happens in competing countries. The research identifying these opportunities has been published for nearly 20 years.
- One approach to capturing some trucking gains would be to make trucking contractors aware of the performance of the best operators at each mill to encourage other contractors to emulate their performance. Many trucking contractors are not aware of the tare weights or average payloads of other producers.
- In most other wood producing regions, some type of effort is made to schedule truck arrivals at mills to attempt to reduce truck waiting times and increase trucking efficiency. Such efforts are rare in the US South, yet we continue to discuss this as an issue. Given our extensive communication systems (cellular phone, Southern Linc, GPS, etc.) we have an opportunity to take action to improve this area.
- Trucking costs are directly and immediately impacted by changes in fuel costs. We found mills and logging contractors buying fuel in bulk through cooperative arrangements in other countries. These efforts not only reduced fuel costs but also often resulted in a fueling station on or immediately adjacent to the mill site thus reducing truck miles driven to find a fuel station.
- Many of our competitors field logging operations for multiple shifts per day and obtain more hours from their equipment prior to replacement.

4.3 Other Issues

- The US South does not have access to the well-funded, consistent research efforts that our competitors in Sweden, Western Canada, and Australia enjoy from Skogforsk, FERIC, and CSIRO. WSRI is a noble effort that should be strengthened and continued, but we have a long way to go to become a peer of these research programs. Until then, we will continue to watch other countries innovate in this area and adopt their technology after they have obtained the early and more profitable returns.
- While the Master Logger programs and other CLE activities have improved training levels in the logger work force, the US South lags other regions in worker training. Most of our productivity gains over the past 30 years have been the result of mechanizing labor-intensive operations (eliminating labor). We may need to rethink our labor training approach if we are to use more advanced equipment in our harvesting force.
- No single study of this duration can do more than take a snapshot of the competitive position of the wood supply system in competing regions. Such comparisons must be performed on a regular basis if their findings are to have the maximum potential value to the industry.

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Estimating internal wood properties of logs based on real-time, NIR measurements of chainsaw wood chips from a harvester/processor*

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Abstract
In many parts of the world log markets are becoming increasingly competitive and complex. Wood properties, such as stiffness, density, spiral grain, and extractives content, are now being considered by log buyers. Assessing these properties in real-time will be a challenge for log supply managers. The utility of near infrared (NIR) technology for predicting wood density in Douglas fir stems was examined. Wood disks were collected from 17 sites around Oregon. Each disk was cut with a chain saw, of similar gauge to that used on mechanized harvesters/processors, to provide saw chips. Near infrared spectra were then obtained for the chip samples. Multivariate techniques were used to correlate wood properties with the NIR spectra. The preliminary research results showed that NIR could be used to predict density. The density predictions should allow logs to be segregated into several density classes.

Keywords: log segregation, sensors, forest harvesting

1. INTRODUCTION

In many parts of the world log markets are becoming increasingly competitive and complex. Where at one time tree species, dimensions, and external quality characteristics (such as branch size, sweep, and scarring) may have been sufficient to specify a log-sort, consideration is now being given to specifying such wood properties as stiffness, density, spiral grain, and extractives content. Accurately assessing these properties in real-time can be a challenge for log supply managers wanting to segregate logs into different product classes based on wood properties. Variables such as stand age and height within a tree have been used in the past as substitutes for accurate measurements.

Mechanized harvesting machines are frequently fitted with computer technology and rudimentary sensor systems for measuring external stem dimensions – usually diameters over bark along the stem and stem length. Research into technologies for measuring stem quality attributes is progressing on a number of fronts with varying levels of success; e.g. acoustics, optical and laser scanning, x-ray, microwave, ultrasound and near infrared (NIR) spectroscopy (Tian 1999, Carter *et al.* 2004, Acuna 2006). Some of these scanning technologies could be integrated into the design of mechanized harvesting systems.

One of the more promising technologies is NIR. Reflectance of near infrared light has been used quite successfully in measuring many wood properties. NIR has been used to measure cellulose content (Raymond & Schimleck 2002), microfibril angle (Schimleck *et al.* 2001), wood stiffness (Kludt 2003, Kelley *et al.* 2004), and pulp yield properties (Sefara *et al.* 2000). A

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 463-472.*

number of authors have concluded that NIR reflectance could be used as a universal method for predicting a wide range of wood properties and applied in genetic selection and log grading (Schimleck *et al.* 2001, So *et al.* 2004).

A five-step process is required for using NIR technology. First, a set of samples with known wood properties is required. Second, the NIR spectra are collected for the known samples. Third, the spectra and the property of interest are correlated using multivariate techniques. Fourth, the reliability of the correlations is validated. Fifth, the validated model can be used to predict the properties of interest for unknown samples. Collecting the spectra and predicting the properties of interest for unknown samples can be done in real-time.

NIR spectra only relate to wood properties up to a few millimeters of depth into the sample. Measurement of wood properties deep within a stem requires internal samples of the wood to be obtained. Chain saw chips, generated as a stem is cut up into logs by a harvester or processor, are a sample of wood through the stem. This leads to the question, "will chain saw chips, and in particular green chain saw chips, be a suitable sample for predicting wood properties based on NIR measurements"?

The objectives of the research reported in this paper were to determine whether NIR spectroscopy could be used to accurately predict Douglas-fir wood density based on three types of samples – green chain saw chips, dry rough chain saw chips, and dry ground chain saw chips. The paper is part of an extensive research that addressed the study of wood properties and use of sensor technology to improve optimal bucking and value recovery of Douglas-fir (Acuna, 2006).

2. METHODS

2.1 Sites and trees selected

In mid-2003, 119 Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) trees were felled at 17 forest sites located in the Coast Range and the Cascade Range of Oregon. The latitude and longitude of the sites ranged from 44^{o} 13' to 45^{o} 36' and from 122^{o} 00' to 123^{o} 35', respectively. The sites were chosen to cover a range of elevations (217 to 996 m) and aspects. Approximately 7 trees were felled at each site and these were selected to cover the range of diameters present. All stands contained second growth Douglas-fir and were of similar age class (45-55 years).

After felling, disks approximately 100 mm thick were cut at regular intervals up each stem: at 0, 1.4, 5, 10, 20, and 30 meters above the base of the tree. The disks were labeled, placed in large bags, and stored in a cold room until they were ready to be used for the wood density determination. Close to 500 disks were collected.

2.2 Sample preparation for NIR spectroscopy

From the total number of disks collected, about 150 were used for NIR spectra measurements. Bark was removed from the edge of each disk. Each disk was then cut with a chain saw, of similar gauge to that used on mechanized harvesters/processors, to provide saw chip samples. Chip samples were collected between 5 and 10 cm from the outer edge of each disk. Samples were divided into three groups: green (100 samples), dry rough (47 samples) and dry ground (50 samples). Chips of the green group were processed just after being collected in the field and were taken from 100 randomly selected wood disks that came from various sites and heights above the base of the tree. Chips from the two dry groups came from 50 randomly selected breast height (1.4 m) disks which had been previously oven-dried. Approximately half of the dry rough chips were then ground into fine powder with a Wiley mill. Samples from the dry ground group were cleaned and their impurities removed.

2.3 Near-infrared measurements

NIR measurements were spread over a period of two years and involved the use of two pieces of equipment; an ASD Field Spec and a NIRSystems 6500.

The NIR measurements for samples in the green and dry rough groups were taken with an Analytical Spectral Devices (ASD) Field Spec (product specifications in www.asdi.com) at wavelengths between 400 nm and 2500 nm using the default parameters. This device uses a fiber optic probe oriented at a right angle to the sample surface to collect the reflectance. The chip samples thickly covered the bottom of a petri dish which was placed on top of a slowly rotating turntable. Thirty scans were collected and averaged into a single average spectrum. Two spectra were taken from each chip sample, which were averaged to have a single spectrum for each sample. This was used to predict the density of the sample. The next step was to reduce the averaging spectra that were collected at 1 nm intervals, to a spectral data set at 5 nm intervals. According to Kelley *et al.* (2004a), averaging the spectral data reduces the size of the spectra matrix and significantly reduces the time required to compute the multivariate models without decreasing the quality of the models.

The NIR measurements for samples in the dry ground group were taken with a Foss NIRSystems Model 6500 at wavelengths between 400 nm and 2500 nm using the default parameters. The powder from the dry ground samples was placed in a standard static ring cup with a sample area of approximately 11 cm^2. Thirty-two scans were collected and averaged into a single average spectrum. The reflectance spectra were converted to absorbance spectra. The spectra, collected at 2 nm intervals on each sample, were only used to predict the density of the sample.

2.4 Wood density measurement

Two slightly different procedures were followed for preparing samples for solid wood density measurements. The disks from which dry chip and dry ground chip samples were taken were first oven dried. Two solid wood samples (about 5 cm wide) were then randomly cut from each disk at about 4-5 cm from the outer edge. The volume of each of the samples was then measured using a water displacement method. Relative wood density (specific gravity) was then calculated as the ratio of dry wood weight to dry volume.

The alternate procedure, used with the disks from which green chip samples were taken, also involved cutting two solid wood samples 4-5 cm from the outer edge. These green solid wood samples were immediately placed in a cold store with an identification tag. The samples were later dried in an oven at 103 degrees C until their weight stabilized (24 to 72 hours). The volume and weight of each sample was then measured and relative wood density calculated. Data on the pith to bark density of each disk was not obtained.

2.5 Multivariate analysis of NIR spectra using Partial Least Square (PLS) procedures

The data sets were divided into calibration sets for developing discriminant models and into prediction sets for evaluating the classification performance of the computed models. The characteristics of the samples in each group, as well as the absorption bands used in the analysis were as follows:

- Green group: Calibration set (65 samples), Prediction set (35 samples), absorption band [502-2500], number of data points (401, every 5 nm of the spectra).
- Dry rough group: Calibration set (24 samples), Prediction set (23 samples), absorption band [355-2495], number of data points (429, every 5 nm of the spectra).
- Dry ground group: Calibration set (25 samples), Prediction set (25 samples), absorption band [400-2500], number of data points (1050, every 2 nm of the spectra).

The analysis to perform chemometric analysis of the spectroscopic data was made through the use of the SAS® partial least squares (PLS) software. As implemented, SAS® (version 9.1) can perform PLS regression type II only (Reeves & Delwiche 2003). While possessing several algorithms for PLSR analysis or for cross-validation and various options for determining the number of factors to use, SAS® does not possess any other spectral pretreatments routinely used in spectroscopy. A number of programs have been written using SAS® macro language to implement 1st and 2nd gap derivatives, Savitzky-Golay derivatives and smoothing, the ability to skip or average spectral data points, to correct spectra for scatter correction by either multiplicative scatter correction or standard normal variate correction with or without detrend, and finally, to mean centre all data prior to regression analysis. Despite the above and other preprocessing techniques that can be used to improve the quality of the PLS models, very often they greatly complicate the ability to provide interpretation of the regression coefficients (Kelley *et al.* 2004a) or provide little to no improvement in predictions (Kludt 2003). Therefore, in this study no preprocessing techniques were used.

The test statistic used for the model comparison was PRESS, the predicted residual sum of squares. A series of analyses by using from one up to fifteen factors were performed, and looking at the results of such runs in terms of the dependent variables explained by the model in the calibration set, but especially in the prediction set. As we were concerned with the predictive ability of the regression model, the number of factors that produced the highest coefficient of determination (R^2) in the prediction set was used and reported in this paper. A calibration model can have a very high coefficient of determination due to overfitting with a high number of latent variables. This can lead to a poor performance of prediction when the model is used with the prediction set.

The quality of the models in the calibration and prediction sets was evaluated with two common measures, R^2 and SEC (SEP for prediction set) (Burns & Ciurzcak 2001). The R^2 value is a measure of the variation of the response variable (wood density) explained by the regression model. For a heterogeneous material such as wood, R^2 values of 0.75 and above are considered good (Kelly *et al.* 2004a). Likewise, the SEC is the standard error of calibration, a measure of the prediction error expressed in the units of the original measurement (Kludt 2003). This is given by the following equation:

$$[1] \qquad SEC = \sqrt{\frac{\sum_{i=1}^{SC}(y_i - y_i)^2}{(SC - n - 1)}}$$

where y_i is the value of the wood property of interest for validation of sample i estimated using the calibration, y_i is the known value of the wood property for sample i (wood density), SC is the number of samples used to developed the calibration model, and n is the number of factors used to develop the calibration model.

On the other hand, the measure of how well the calibration predicts the wood property of interest for a set of unknown samples that are different from the calibration test set is given by the standard error of prediction (SEP):

$$[2] \qquad SEP = \sqrt{\frac{\sum_{i=1}^{SP}(y_i - y_i)^2}{(SP-1)}}$$

where y_i is the value of the wood property of interest for sample *i* predicted by the calibration, y_i is the known value of the wood property (density) for sample *i* , and SP is the number of samples in the prediction set.

3. RESULTS

3.1 Wood density

Table 1 gives a statistical summary of wood density for the calibration and prediction data sets for the three sample types – green, dry rough, and dry ground chain saw chips.

Table 1. Range and standard deviation (SD) of wood density (kg m^{-3}) by sample type, for calibration and prediction data sets.

Sample type	Calibration set				Prediction set			
	Min	Max	Mean	SD	Min	Max	Mean	SD
Green chain saw chip	315	489	399	41.7	335	509	414	43.8
Dry rough chip	371	490	433	29.8	359	509	441	40.4
Dry ground chip	381	476	436	26.5	359	499	432	40.3

The minimum density for the calibration set corresponded to the green group (315 kg m^{-3}), while the maximum density was associated with the dry rough group (490 kg m^{-3}), which was very close to that of the green group (489 kg m^{-3}). Averages densities were higher in both dry ground and dry rough groups (436 and 433 kg m^{-3}, respectively) with more than 30 units of difference with the green group (399 kg m^{-3}). A similar tendency was found in the prediction set. The minimum density in this set corresponded to the green group (335 kg m^{-3}) and the maximum density is found in both the green and the dry rough group (509 kg m^{-3}). Also, standard deviations were considerably higher in the prediction set than in the calibration set. The green samples came from heights ranging between 0 and 30 m within selected trees while the dry samples were only taken from breast height disks. Wood density tends to decrease with height in a tree, so it could be expected that the dry samples had higher average densities than the green samples.

3.2 Variation of NIR spectra

Peaks of absorbance for all three sample groups (green, dry rough, dry ground) were found at about 1500, 2000 and 2500 nm.

The spectral curves for the green chain saw chip group are shown in Figure 1. They illustrate the difference between the NIR spectra for three representative samples of low (315kg m^{-3}), average (407 kg m^{-3}), and high (509kg m^{-3}) densities in terms of their general absorbance.

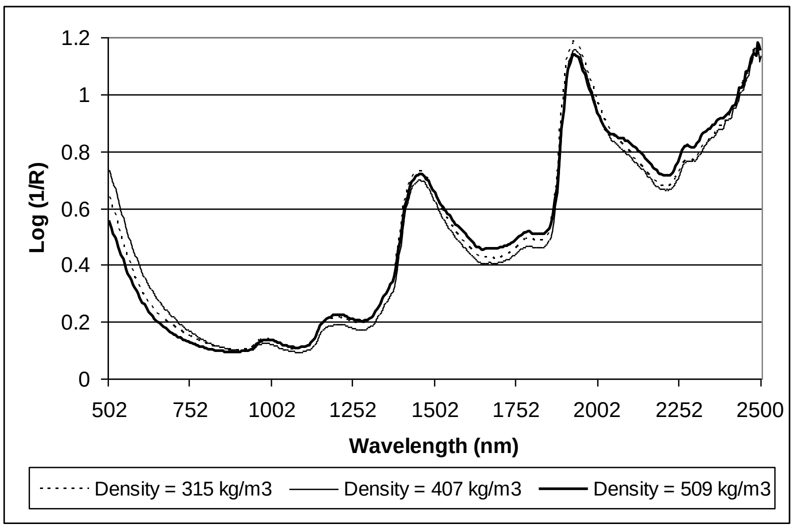


Figure 1. Variation in near infrared (NIR) spectra collected from green chain saw chip samples for different values of basic density.

Figure 1 shows that the high-density sample has slightly less absorbance than both the low and average density samples at wavelengths below 1000 nm. For the rest of the spectral range (1000-2500 nm) the high-density sample has the highest absorbance – most notably in the 1500-1850 nm and 2000-2350 nm ranges.

The spectral curves for the dry rough group show a lower absorbance for all spectra in comparison to the green chain saw chip group. This tendency is confirmed by previous reports (Schimleck *et al.* 2003); however in their studies the difference between green and dry samples is more notable than that found here. This may be due to the characteristics of the dry rough samples used. Other differences between the spectra for the dry rough group and the green group include: a possible reversal of absorbance trends (absorbance for high density samples being higher at wavelengths below 1000 nm and lower at wavelengths above 1900 nm), and the presence of more "noise" and irregularities in the dry rough spectra.

Absorbance values for the dry ground group were intermediate between those found in the green and the dry rough groups. When compared to the other two groups (green and dry rough), there appeared to be no differences among the high, average and low density samples. There also appeared to be no significant differences between the dry rough and dry ground groups over the 400-2500 nm spectral range.

3.3 Development and application of PLS regression calibrations

Summary statistics for the wood density calibrations are presented in Table 2. The calibration developed for wood density in each group of samples gave good results, with values of R^2 ranging from 0.89 to 0.95. Wood density calibrations developed using NIR spectra obtained from the dry rough group gave better results compared with the calibrations developed using spectra obtained from the green and the dry ground groups (Figure 2).

Another interesting aspect of the calibration procedure is the difference observed in the number of factors in each group that gave the best results. While just three factors were necessary in the dry rough group to reach the best R^2 in the prediction set, twelve factors were necessary for the green and dry ground groups. Clearly, however, the R^2 in the prediction set was lower for the dry rough group than for the other two groups.

Table 2. Summary of calibrations with partial least squares regression developed for basic density using spectra collected from the samples.

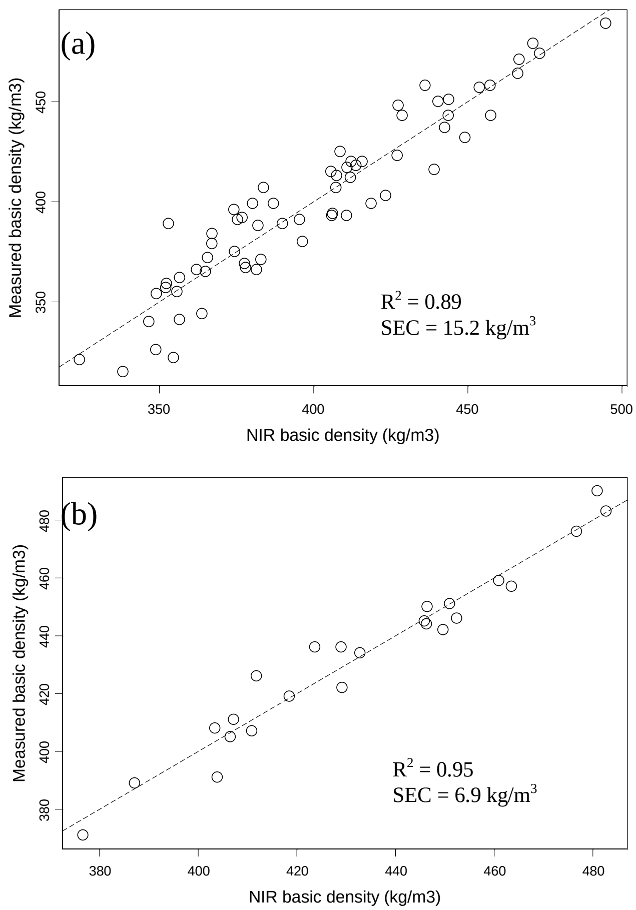
Sample type	Calibration set			Prediction set	
	No. of factors	R^2	SEC	R^2	SEP
Green chain saw chip	12	0.89	15.2	0.74	22.7
Dry rough chip	3	0.95	6.9	0.56	27.4
Dry ground chip	12	0.90	11.8	0.85	15.7

When calibrations were used on a separate prediction set for each sample group it was found that calibrations developed using spectra collected from the dry ground group gave the strongest prediction statistic, with a R^2 of 0.85. Conversely, the weakest relation was found in the dry rough group with a R^2 of 0.56. The prediction values of R^2 for the linear regressions are shown in Table 2, and they represent the proportion of variation in the independent prediction set that was explained by the calibration model.

In general, predictions of the density in each sample type were satisfactory, but the R^2 values were lower than the R^2 obtained for the calibration sets, with the greatest reduction occurring for the dry rough group. SEP values (15.7-27.4 kg m^{-3}) were considerably higher than the SEC values (6.9-15.2 kg m^{-3}). The dry rough group showed the greatest difference between the SEP and SEC values. The presence of some outliers in the dry rough sample group did not permit a good fit of the data. These outliers may be associated with either some mechanical errors inherent to the NIR spectrometer measurements or to the measurement and calculation of the density of the wood samples. These outliers and sources of error may help to explain the high values of SEP found for the dry rough and green groups.

4. DISCUSSION AND CONCLUSIONS

The usefulness and potential of NIR spectroscopy for predicting wood density of Douglas-fir based on chain saw chip samples has been successfully demonstrated. Calibration models were found to perform best for both dry rough and dry ground samples; SEC's expressed as percentage of the mean were 1.6% and 2.7% respectively. On the other hand, prediction models performed best for both the green and dry ground samples; SEP's expressed as percentage of the mean were 5.5% and 3.6% respectively. The standard errors of the predictions using the dry rough samples were relatively large compared with the standard errors of the other two groups. We believe, however, that removing a couple of outliers would considerably improve the prediction capability in the dry rough group and reduce the standard errors observed.



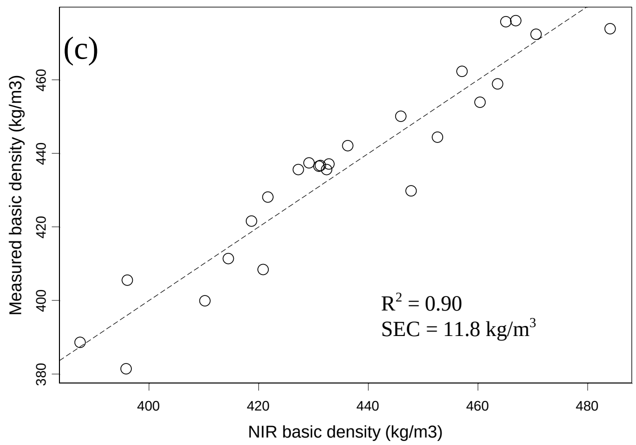


Figure 2. Relationships between measured values and values predicted with near infrared (NIR) spectroscopy for (a) green chain saw chip samples, (b) dry rough chip samples, and (c) dry ground chip samples. Results presented are those obtained for calibration.

R^2 values for NIR-predicted basic densities ranged from 0.56 for the dry rough Douglas-fir chip samples to 0.85 for the dry ground chip samples. The green chainsaw chip samples had an intermediate R^2 value of 0.74. These R^2 values are similar to those reported by So *et al.* (2002) and by Schimleck et al. (2003) for loblolly pine solid wood; R^2 values of 0.67 and 0.74 respectively.

Kelley *et al.* (2001) have reported that NIR measurements of green solid wood samples can be used to accurately predict dry wood stiffness for poplar. Schimleck *et al.* (2003) found that NIR measurements of green wood can be used to predict air-dry wood density for loblolly pine. The results of our study confirm their work and reveal the possibility of using NIR spectroscopy of green chain saw chip samples to predict wood properties (such as density) in real time, negating the need to dry samples prior the analysis. These results open the doors to the use of this type of technology for log segregation by mechanized harvesting equipment (e.g. harvesters).

NIR spectra on the green chain saw chip group in this study were gathered from a loosely packed sample in a petri dish on a slowly revolving turntable. While it would be possible to collect "grab" samples of green chain saw chips for NIR measurement in this manner it would be preferable to undertake the measurements on green chips that are being ejected from the log as it is being cut. This would mean obtaining measurements on very, dispersed chips moving at high speeds. Further research will be required to determine whether reliable measurements of wood density can be made from green chips ejected from a log as it is being cut.

To operate in "real-time" NIR measurements would need to take only a few seconds. In this study both spectrometers were using an average of about 30 scans to produce the spectral curves for the 400-2500 nm range. Scan rates for one spectrometer were 10 scans per second and for the other spectrometer 1.8 scans per second, implying overall scan times ranging from 3 to 17 seconds. Kelley *et al.* (2004a) have demonstrated that some wood properties, such as strength and stiffness, can be predicted with only a slight decrease (~ 0.05) in the R value, when a reduced spectral range (650-1050 nm) is used. They comment that the reduced spectral range would allow the use of much smaller, faster, lighter and less expensive spectrometers.

From this study we can conclude that:

(1) Useful calibrations for Douglas-fir wood density can be developed using NIR spectroscopy of chain saw chip samples.
(2) Green chain saw chip samples could provide NIR estimates of wood density that are only slightly degraded from those coming from dry ground chip samples.
(3) Further work is required to determine whether the promise of real-time, cost effective measurements of wood density (and other wood properties) using NIR technology is valid.

5. ACKNOWLEDGEMENTS

Support for this work has come from the US Department of Agriculture Center for Wood Utilization Research Grant. We would also like to acknowledge the assistance of Dr. Stephen Kelley who was working for the National Renewable Energy Laboratory when many of the NIR spectra were collected.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

A 3D Optimal Bucking System for Central Appalachian Hardwood Species*

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Abstract

An optimal tree-stem bucking system was developed for central Appalachian hardwood species using 3D modeling techniques. ActiveX Data Objects were implemented via MS Visual C++/OpenGL to manipulate tree data which were supported by a backend relational data model with five data tables for stems, grades and prices, logs, defects and stem shapes. Network analysis algorithm was employed to achieve the optimal bucking solution with different alternative stage intervals. Once all the data associated with a tree-stem were retrieved, a 3D tree-stem could be displayed for either optimal or manual bucking based on the user's options. Log rules of Doyle and International ¼" were used to compute the log volumes during the bucking processes. The grading and pricing system was modeled for some major central Appalachian hardwood species based on the mill survey. The bucking system can be used as a training tool or compiled for installation on a handheld or field PC to improve the hardwood utilization in the region.

Keywords: optimal bucking, network analysis, dynamic programming, 3D modeling, Appalachian hardwoods.

1. INTRODUCTION

Optimal tree-stem bucking is a complex process that requires simultaneous considerations of species, quality of stem, log length, diameter, log price, and other factors (Sessions 1988, Pickens et al. 1997, Wang et al. 2004). During the last six decades, optimal Bucking has been addressed by many researchers. Since the 1960s, computer modeling techniques associated with tree-stem bucking have been introduced by using mathematical programming (Wang et al. 2004), including linear programming, dynamic programming, network analysis, and branch-and-bound strategies (Smith and Harrell 1961, Pnevmaticos and Mann 1972, Sessions 1988, Sessions et al. 1989, Bobrowski 1990). These models were primarily used to solve a single stem optimal bucking problem. Stand and forest level optimal bucking/planning problems, however, considering transporting cost, resource and log distribution constraints, was addressed using Dantzig-Wolfe decomposition method (Eng and Daellenbach 1985, Mendoza and Bare 1986), two stage methods, heuristic techniques like tabu search (Laroze and Greber 1997, Laroze 1999) , fuzzy logic (Kivinen and Uusitalo 2002), and genetic algorithm (Kivinen 2004).

Several optimal bucking systems have been developed for training, real-world application, or research purposes. A VISION decision simulator was developed to apply

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 473-482.*

dynamic programming in tree-stem bucking at Weyerhaeuser Company (Lembersky and Chi 1984, 1986). Field buckers could build their bucking decision skills with VISION. The optimal decisions generated by VISION could be later used as new bucking instructions. Using dynamic programming, Geerts and Twaddle (1984) developed AVIS (assessment of value by individual stems) in New Zealand to maximize the single tree-stem value. Two mechanized bucking operations in southeastern United States were compared with the optimal value computed by using AVIS (Boston and Murphy 2003). Conradie et al. (2003) also used the AVIS to determine the value recovery with harvesters in southeastern U.S. pine stands. They found a 6% loss for a final harvesting and 42% loss for a thinning operation. BUCK, developed at Oregon State University (Sessions 1988), is an interactive tree optimizer using network analysis that considered alternative mill prices, transport distances and equipment capability. Garland et al. (1989) compared value recovery from manual log bucking and from using BUCK on a HP handheld computer. They reported that 14.2 and 11.9% value increases could be achieved by using BUCK. BUCK has also been tested on a mechanized harvester, where 7.5% of the total value recovery was reported (Olsen et al. 1989). HW-BUCK was developed by Pickens et al. (1993) for optimal bucking of northern hardwood species, and was designed to help a trainee develop heuristics to select the bucking pattern for a tree-stem (Frayer et al. 1995). A database containing actual shape information of 150 northern hardwood trees is specifically used for training buckers. Buckers could make their bucking decisions based on a 2D tree-stem and compare their decisions with the computer-generated patterns. It was also evaluated for a hardwood value recovery study in southern Appalachia (Haynes and Visser 2004).

In central Appalachia, difficult terrain and hardwood species make harvesting and bucking even more difficult. Ground-based harvesting is still the dominant system. Bucking with a chainsaw or a sawbuck at landings was a typical practice in the region (Milauskas and Wang 2006, Wang et al. 2006). Most of the loggers were not well trained for bucking. Hardwood species usually have more defects and sweeps than softwoods and their values varied greatly by species, grades, and dimensions. Based on our log price survey in the central Appalachian area, a log's value can vary up to 50% even for the same grade with different length and diameter combination. For different sawmills, the grading rule and log prices are also different. Therefore, there is a great need to develop a flexible bucking system with powerful frontend and backend to enhance the optimal bucking in central Appalachia. Specifically, the bucking system should meet the following requirements: (1) easy to use: most of the buckers do not have much computer knowledge; (2) virtual environmental simulation: the system should provide the bucker with a near virtual bucking situation as similar to that which they are doing in the woods and allow the user to manipulate the shapes and defects of a tree-stem; and (3) user defined grading rules and price matrixes that will allow users to add/edit grading rules and price matrixes for different saw mills.

2. SYSTEM DESIGN AND STRUCTURE

The optimal bucking system consists of four major components: tree stem data manipulation, 3D modeling, bucking optimization and data storage. Component object model (COM) was employed to integrate the system that was designed by using the principle of Object-oriented programming (OOP). The system was programmed with Microsoft Foundation Class

(MFC) and Open Graphics Library (OpenGL). MFC provides user friendly interface and can be easily transplanted to any other Windows applications while OpenGL offers great power to create 3D virtual bucking environment. The 3D objects can been rotated, scaled, and transformed by performing OpenGL transformation (Figure 1).

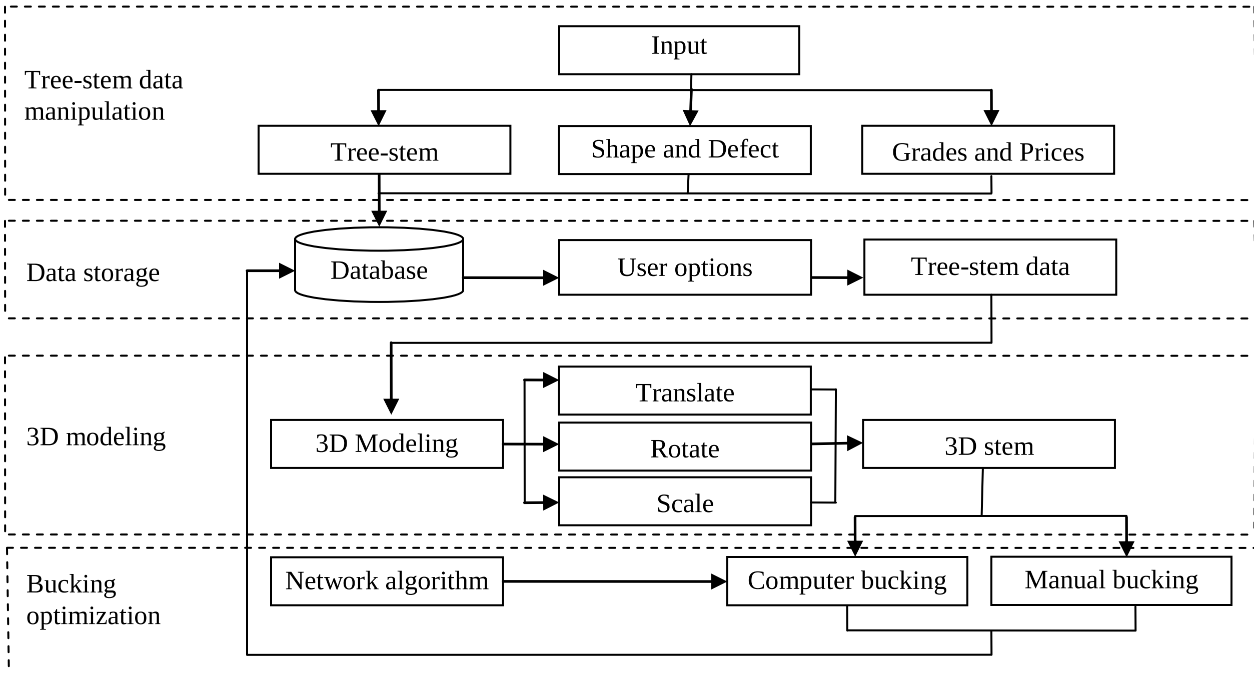

Figure 1. Flow chart of the optimal bucking system.

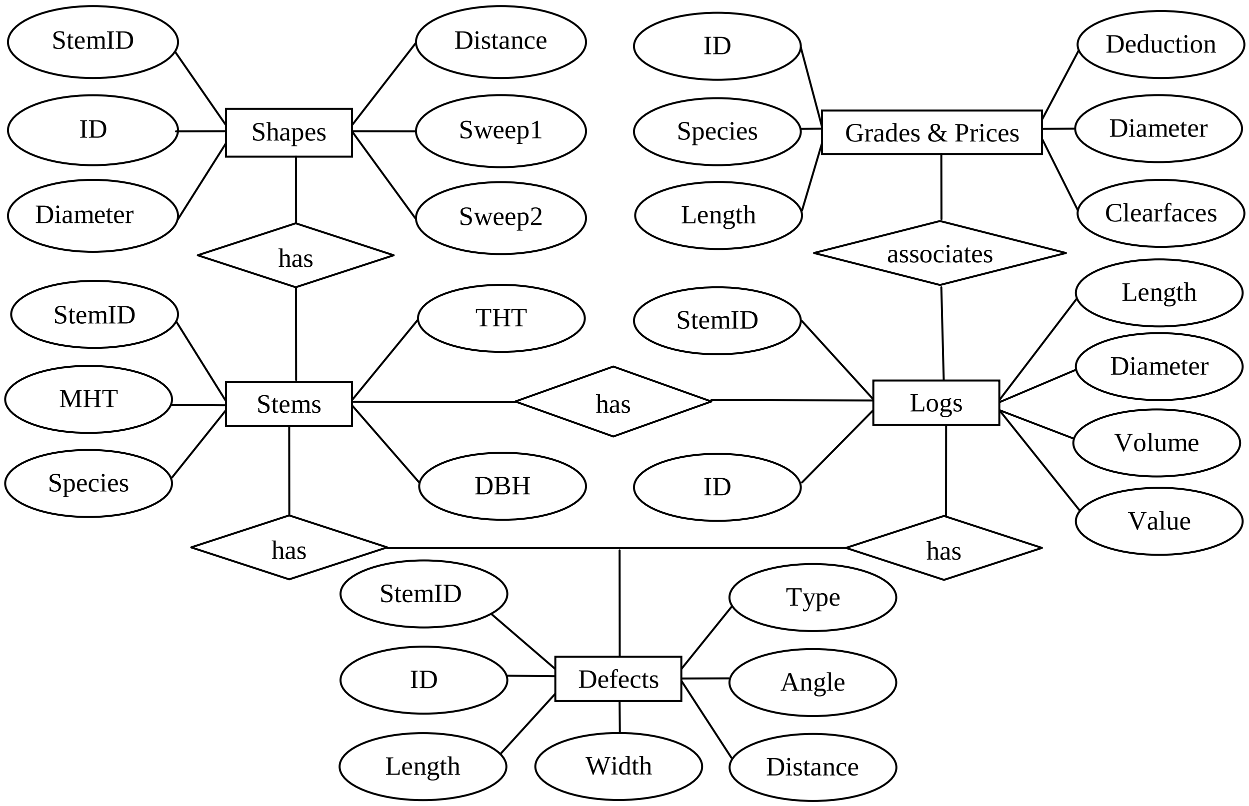

Figure 2. Entity-Relationship model of the optimal bucking system.

Entity-Relationship (ER) data model is used to store the optimal bucking data, which was implemented through five entity types or data tables including stems, shapes, grades & prices, defects, and logs (Figure 2). Five relationships were built in the model to relate these five entity types. Each entity type has its attributes such as StemID and Species for Stems.

ActiveX Data Object (ADO) was employed to access the data in the database. ADO provides a user-oriented method of data access and serves as a layer between OLE DB and the client, which enables indirect access to OLE DB provider. This layer can also help the programmer make easy use of OLE DB functions or properties without knowing the complexity behind the C++ class templates (Sarrett 1998, Sphar 1999). The ADO employed in the optimal bucking data model contains seven basic objects: connection, recordset, command, error, field, property and parameter. These objects are interrelated to each other and have their own properties and methods (Figure 3).

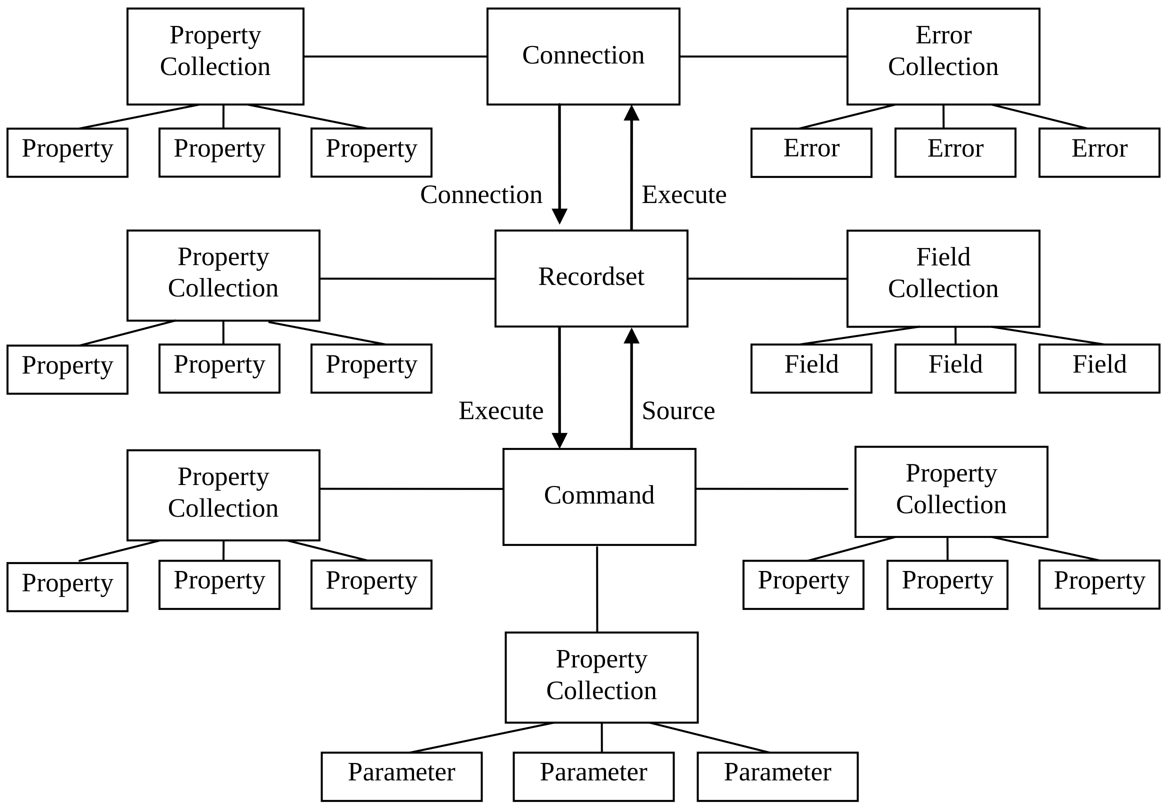

Figure 3. ADO objects and their relationships.

3. SYSTEM MODELING

In order to provide the user with a realistic tree-stem, 3D modeling techniques were used together with some OpenGL primitives drawing functions. The 3D tree-stem was composed of simple triangle strips and the strips were filled with stem images, such as bark or butt end image. The user can perform rotate, translate and scale functions to get a better understanding of the stem superficial characteristics (Figure 4).

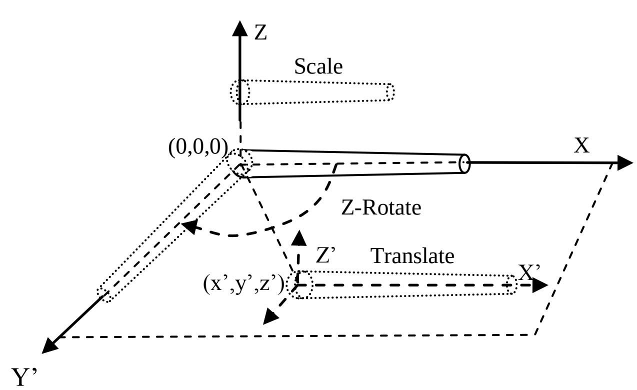

Figure 4. Modeling transformation of a 3D tree-stem.

Rotate function is invoked by calling glRotate (α, x, y, z) which generates the rotation matrix by defining the axis to be rotated about (x-axis, y-axis or z-axis) and the degrees to be rotated (α). The generic matrix of rotation α angle around the x-axis can be expressed as (Woo et al. 2000):

$$R_x(\alpha) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1)$$

Let V = $(x,y,z,1)^T$ be a vector before rotation, which contains the coordinates of a point and 1 for homogenous coordinate. If V is rotated by α degree around x-axis, the rotated vector V' can be expressed as:

$$V' = R_x(\alpha) \times V$$

$$\begin{bmatrix} x' \\ y' \\ z' \\ 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}_{R_x} \times \begin{bmatrix} x \\ y \\ z \\ 1 \end{bmatrix} = \begin{bmatrix} x \\ y\cos\alpha - z\sin\alpha \\ y\sin\alpha + z\cos\alpha \\ 1 \end{bmatrix} \qquad (2)$$

So $V' = (x', y', z', 1)^T = (x, y\cos\alpha - z\sin\alpha, y\sin\alpha + z\cos\alpha, 1)^T$. Let the coordinates of the vertices of a triangle (basic unit for a tree-stem) be (x_1, y_1, z_1), (x_2, y_2, z_2), (x_3, y_3, z_3), respectively. The coordinate matrix for this triangle after rotated by α degree around x-axis can be expressed as:

$$\begin{bmatrix} x_1' & x_2' & x_3' \\ y_1' & y_2' & y_3' \\ z_1' & z_2' & z_3' \\ 1 & 1 & 1 \end{bmatrix} = R_x(\alpha) \times \begin{bmatrix} x_1 & x_2 & x_3 \\ y_1 & y_2 & y_3 \\ z_1 & z_2 & z_3 \\ 1 & 1 & 1 \end{bmatrix} \qquad (3)$$

$$TS' = R_x(\alpha) \times TS$$

Where, TS is the coordinate matrix for one triangle before transformation and TS' is the coordinate matrix for this triangle after transformation. Similarly, the coordinate matrices for the triangle strip can be rotated around y-axis and z-axis. The scale and translation are performed by calling glScale (S_x, S_y, S_z) and glTranslate (dx,dy,dz) functions. S_x, S_y, S_z are the scales to x, y, z coordinate of the stem while dx,dy, dz are the units of distances to be translated along the x-axis, y-axis and z-axis, respectively.

Network analysis technique (Dykstra 1984, Nasburg 1985, Sessions 1988, Hillier and Lieberman 1995) was implemented in the system to generate the optimal bucking patterns. A series of potential cutting points are defined based on a given stage interval and denoted by X_i (i=0,1, 2,…, n). The distance between two adjacent cutting points is the stage interval and the first potential cutting point is the origin and the last potential cutting point is the destination along a tree-stem. The "shortest" path form the ith cutting point (X_i) to the origin (X_1) (i = 1, 2,…) needs to be achieved and this procedure is repeated until the nth cutting point – the destination(X_n) is reached. The maximum value for each cutting point is presented by V_i (i=1,2,…n). Each solved node that is directly connected by a link to one or more unsolved nodes (X_j) provides one candidate-the unsolved node with the "shortest" connection link. The value between one solved node and one unsolved node is defined as the weight W(j,i) for this arc. The whole process can be expressed by the following equation:

$$\begin{cases} V = \max(V_i) \\ V_i = \max\{V_j + W(j,i)\} \\ i = 1,2,...,n \\ j = 1,2,...,i-1 \end{cases} \tag{4}$$

Two major log rules were used in the system: Doyle and International ¼ inch. Grading rules and price matrixes were derived based on a mill survey in the central Appalachian region. Logs are usually classified as veneer, prime, select common and under common class according to their sizes, species, and defects. Since differences exist among mills, the system allows the user to define his/her own grading and pricing system.

Currently, the minimum 8 feet log and 10 inch small end diameter were implemented in the system. For all the log grades, 3 inch trim allowance is required. Log length will be rounded down to the nearest feet length. For example, log with length of 15.2 feet will be measured as 14 feet with trim. Log with length of 15.4 will be measured as 15 feet with trim. The maximum log length allowable is 16 feet. Any logs with length greater than 16 will be measured as 16 feet. A scale deduction of 1 inch diameter is made for every 3 inches of sweep. A scale deduction of 1 inch diameter is also made for every 3 inches in diameter of a hole, rot, or shake in the end of the log. Logs that have more than 50% scale deduction are considered cull.

4. BUCKING SYSTEM APPLICATION

A total of 160 trees of two major species red oak and yellow poplar were measured for comparisons with manual bucking patterns during August 2005 and March 2006. Stems were measured with diameter calipers and 100 foot tape. Outside bark diameters were measured at every 4-foot interval and rounded to nearest inches. Total Length and merchantable lengths were measured and rounded to nearest feet. Defects were recorded for each stem and their sizes were rounded to nearest inches. To measure sweeps, two measurement sticks were nailed on both ends of a surface of a tree-stem and a string was tightened to these two sticks at the same height to the surface of the stem. This height is called base height. At each 4-foot interval, the distances from the string to the surface of the stem were measured and subtracted from the base height. Then turning the sticks and string 90 degrees from the previous position, the above procedures were repeated until all the sweeps were measured.

First, the user selects a tree-stem, then he or she can view all the defects and shapes information associated with the selected stem. A 3D tree-stem with basic stem data is then displayed (Figure 5). For example, a selected tree-stem of red oak has a total length of 47 feet, butt diameter 22 inches, top diameter 10 inches, maximum sweep 31 inches, and a total of 10 defects (Figure 5). Bucking options and log scaling rules can be selected via radio button or checkbox controls. When optimal bucking method is chosen, the users also then need to select a stage interval for network analysis algorithm. Both manual and optimal bucking can be performed by using mouse, keyboard, or six built-in command buttons on the lower left corner of the stem display area. The users can use these functions to rotate, enlarge, zoom, and move the stem. This stem was manually bucked into four logs: 16-foot select, 10-foot common, 10 below and 10 foot cull logs (Figure 6). The total value of this tree-stem is $151 based on the default price matrix and grading rules. The last 10 foot log has no value because its top diameter less than the minimum required log diameter and it is graded as cull with no value. If user is satisfied with the bucking results, he or she can save the bucking results to the database.

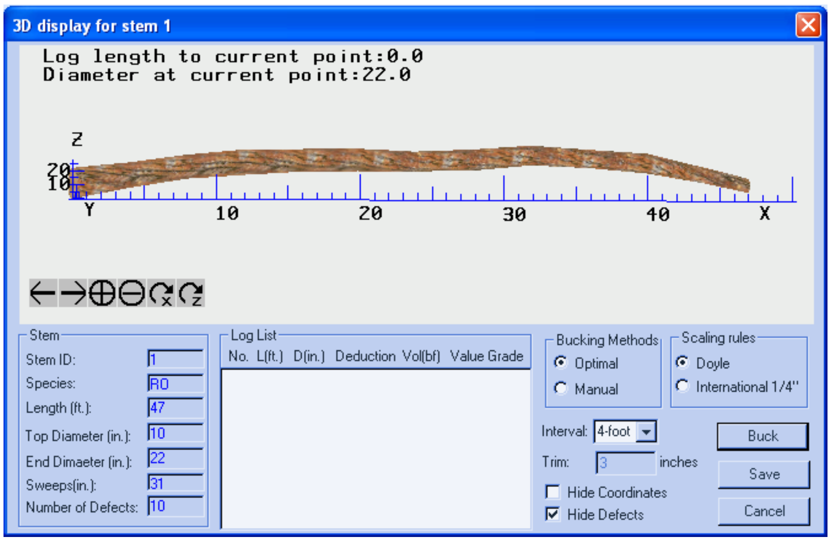

Figure 5. A 3D tree-stem with hidden defects for bucking.

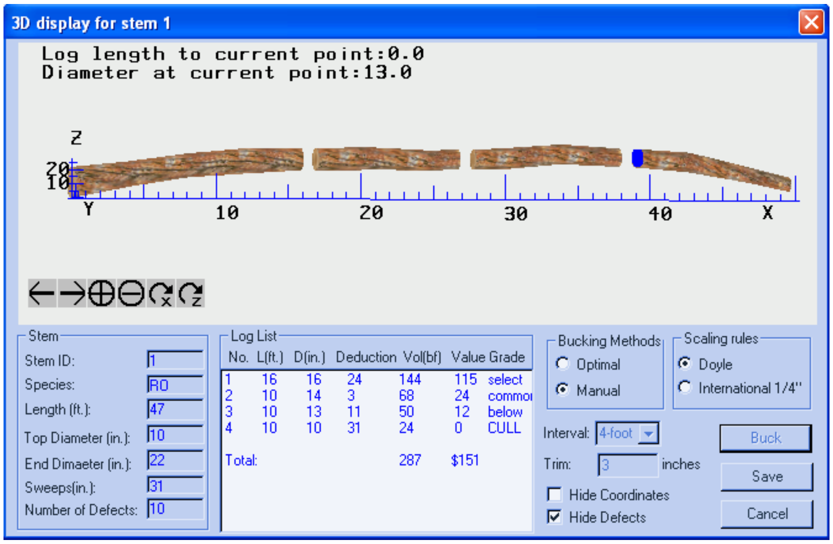

Figure 6. 3D logs of manual bucking.

A subset of 30 red oak tree-stems were concurrently analyzed and compared for this study using this optimal bucking system. The total length of these stems ranged from 33 to 55 feet, with an average of 43 feet. Their butt diameters were between 11.8 and 18.8 inches with an average of 14 inches. The stems also had an average sweep of 13.3 inches and 7 defects per stem.

Each stem was bucked optimally with 1-inch, 4-inch, 1-foot, and 4-foot stage intervals. The optimal bucking results were compared with the bucking results recorded from the field. The results indicated that the optimal bucking can gain 26.6%, 40.0%, 42.5% and 43.1% more value with 4-foot, 1-foot, 4-inch and 1-inch intervals compared to the manual bucking (Table 1). The average running time of optimal processes for 4-foot, 1-foot, 4-inch and 1-inch intervals are 18, 201, 1767 and 19354 milliseconds, respectively, on a PC with Pentium 4 2.26GHz CPU, 1.0GB RAM, and 60GB hard drive.

Table 1. A brief comparison of optimal and manual bucking for 30 trees.

	Manual bucking	Optimal bucking – stage interval			
		1-inch	4-inch	1-foot	4-foot
Average log length (ft.)	12.4	10.7	10.6	10.6	10.6
Average log LED[a] (in.)	14.1	14.3	14.1	14.1	14.0
Average log SED[b] (in.)	12.4	12.9	12.7	12.8	12.7
Average volume per log (bf.)	55.7	54.5	53.5	53.6	53.9
Average log value ($)	19.3	25.7	24.9	24.2	22.8
Average number of logs per stem	2.5	2.6	2.7	2.7	2.7
Total value recovery ($)	1429	2045	2037	2000	1809
Percentage increase (%)	-	43.1	42.5	40.0	26.6
Average stem value ($)	47.6	68.2	67.9	66.7	60.3
Average performance time per stem (millisecond)	-	19354	1767	201	18

[a]LED = large end diameter.

[b]SED = small end diameter.

5. DISCUSSION

The optimal bucking system developed in this application adopted component object modeling techniques (COM) with object-oriented programming and 3D graphs. The system can be installed on a handheld field PC or a desktop PC located in a centralized log yard to improve central Appalachian hardwood utilization. It can also be used as a training tool for students or loggers.

Brief comparisons indicate that the optimal bucking can gain 26.6 – 43.1% more value per stem. The running time of optimal bucking process is greatly affected by the length of stage interval. As the stage interval decreased from 4 feet to 1 inch, the running time increased 1075 times from 18 to 19354 milliseconds. Therefore, the appropriate, smaller stage interval for optimal bucking should be further evaluated. The system allows the user to buck one tree-stem at a time. In order to automate the process, optimal bucking of groups of trees selected will be incorporated into the system. When performing group bucking, the computer execution time and memory management become the key factors that need to be managed efficiently.

Detailed economic comparisons between optimal and manual bucking will be conducted based on 160 trees collected in the region. The cost and profit comparisons will be further analyzed by species and log dimension. The interrelationship among value recovery, species, stem dimensions, defects, and grading rules also needs to be addressed in the near future. A future study will also concentrate on the comparisons between this optimal bucking system and HW-BUCK for bucking Appalachian hardwood species.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Maximum value throughout the wood supply chain: the RAID concept*

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Abstract
Maintaining or enhancing value throughout the solid-wood supply chain, from the stump to the client facility, is essential to enable the forest industry to manufacture the highest-quality products. FERIC promotes the use of a concept known as RAID to achieve this objective: Reduce stem and log breakage; Allocate the right log to the right mill at the right time; Increase fiber and value recovery; and Decrease value losses during wood storage. This paper describes the results and applications of several FERIC research initiatives under each of these four axes of the RAID concept. Reducing breakage through best operating practices (full-tree equipment) and the use of swing-boom skidders are discussed. Allocating the best log resulting from appropriate bucking scenarios and product sorting is also described. Project results on maximizing value recovery by means of optimized bucking in both softwood and hardwood operations are also provided. The paper concludes with an overview of the benefits of wood storage under snow and the integration of wood storage parameters in the Opti-Stock model.

1. INTRODUCTION

Maintaining or enhancing value throughout the solid-wood supply chain, from the stump to the client facility, is essential to enable the forest industry to manufacture the highest-quality products possible. In recent years, the Forest Engineering Research Institute of Canada (FERIC) has maintained an extensive research program in the area of maximizing the fiber quality and value obtained from forest operations. This program has led to the development of new practical knowledge that has been synthesized and distributed through a variety of technology-transfer media, such as reports, best-practices guides, downloadable Flash presentations, spreadsheets, and more advanced software tools.

FERIC has developed the RAID concept to provide a framework that integrates these products to help managers ensure that their operations use best practices to maintain fiber quality and enhance value. RAID stands for the following components: **R**educe stem and log breakage; **A**llocate the right log to the right mill at the right time; **I**ncrease fiber and value recovery; and **D**ecrease value losses during wood storage. Because extensive literature already exists on the topic of the fiber quality obtained from woodlands operations, this paper will focus on the research results and applications developed by FERIC for use in eastern Canadian operations under each of the four components of the RAID concept.

Reduce stem and log breakage

Operating practices and equipment selection can have a huge and sometimes critical impact on quality by their effects on log or stem breakage or damage during any of the

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 483-492.*

harvesting and delivery phases. FERIC has conducted numerous studies of breakage during forestry operations, and the results obtained prior to 1998 were summarized by Favreau (1998).

During these studies, data were collected both on the levels of breakage occurring and on the impact of various operating techniques on these levels. This information was summarized in two downloadable Flash presentations designed to present best practices for operations using full-tree to roadside equipment. One presentation deals solely with feller-bunchers, recognizing that the machine working at the head of the production chain deserves the most attention. The other presentation covers skidding and roadside delimbing. The best practices covered by both presentations (available via the Solutions section of FERIC's Web site, www.feric.ca) were designed to be easy for field staff to understand and implement.

For feller-bunchers, best practices to minimize stem breakage include:

- Replace or rotate damaged teeth immediately. Andersson (2003) found that during a winter operation, 29.5% of the stems showed butt damage that caused a volume loss; this proportion decreased to only 9.1% when operating the felling head with new saw teeth.
- Avoid exceeding the tree accumulator's holding capacity prior to bunching.
- Avoid horizontal pressure between the crowns of cut trees held in the accumulator and the crown of the tree being cut.
- Avoid repositioning trees that have already been bunched on the ground.
- Work smoothly and avoid jerky maneuvers.

Skidding represents another harvesting phase in which breakage frequently occurs if care is not taken. Stems stressed during the felling phase can break completely if mishandled during skidding. For example, decking at roadside with grapple skidders is a major cause of breakage, whether as a result of traveling directly on the log decks or pushing stems from the side using the skidder's dozer blade to make room for additional loads. In one study conducted by Légère (2001), 48% of the stems exhibited some form of damage resulting from these practices. He found that the number of stems showing some level of breakage could be reduced by half if skidders delivered the trees directly to the delimbers at roadside in an integrated system (also called "hot logging") that eliminates decking of stems by means of a "just in time" delivery system.

Recently, skidders equipped with grapples mounted on pivoting booms, such as the Morgan SX-706, have become more popular in eastern Canada (Figure 1). A recent study found that this technology could reduce stem breakage by 30% compared with using traditional grapple skidders because loads can be swung sideways onto the log decks at roadside, thereby eliminating the need to climb onto the log decks with the machine during unloading (Gingras and Plamondon 2005).

Figure 1. A skidder equipped with a swing-boom grapple unloading at roadside.

Favreau (1998) also reported that clambunk skidders produced 25% fewer broken stems than grapple skidders in the same operation because these large-load machines typically do not climb over the piles at roadside.

Roadside delimbing of trees can also lead to significant breakage if operating practices are poor. Integration of the skidding and delimbing operations is the preferred option for the delimbing phase because it facilitates extraction of stems by the delimber. When trees are decked at roadside in a separate prior operation, they often become tangled and compressed, making it difficult for the delimber to pull out individual stems, resulting in breakage and fiber loss. In addition, care must be taken when operators choose to delimb multiple stems to increase their productivity, and when handling salvaged material such as fire- or insect-killed trees, which are highly susceptible to breakage.

Allocate the right log to the right mill at the right time

Maintaining undamaged logs or tree-length stems during the logging operation is critical, but directing the right product to the right mill at the right time is also important in maximizing fiber quality. The reality of today's harvesting operations is that operators are responsible for producing a wide diversity of products to meet a similarly wide range of specifications, for a large number of customer mills and delivery schedules. These logistics may be further influenced by economic parameters such as the need for just-in-time delivery and the need to restrict inventory levels. Although satellite merchandizing yards are used in some parts of eastern Canada (especially for hardwoods), the majority of product sorting takes place during the actual harvesting operation. In some cases, sorting is concentrated in a single phase, such as roadside delimbing, whereas in other cases, it is spread throughout the production chain. FERIC has conducted a number of sorting studies over the years to identify optimal sorting scenarios.

Table 1 presents the productivity losses (%) measured during these studies, as a function of the number of sorts versus producing only a single product. This information was generated by pooling a number of results from studies by FERIC and other researchers (Bjurulf 1992; Brunberg and Arlinger 2001; Gingras 1996; Gingras and Godin 1997, 2001; Gingras and Soucy 1999; Gingras and Favreau 2002).

Table 1. Effect of sorting on machine productivity (% loss compared with one product).

	Number of products separated			
	2	**3**	**4**	**5**
Feller-bunchers	5–10	9–11	15	n.a.
Delimbers	5–10	10–15	15–25	n.a.
Harvesters and processors	1–4	2–8	3–12	4–16
Forwarders	3–8	8–13	12–20	16–27

To optimize the delivery of properly sorted logs and stems to the right mills, FERIC has developed computer software to help its members compare harvesting and delivery scenarios. One of these tools, called *Interface-Map*, allows users to import digitized maps to produce harvesting and transportation simulations based on actual spatial and forestry data for the various blocks to be harvested. Figures 2 and 3 provide screenshots from the software using a hypothetical supply situation.

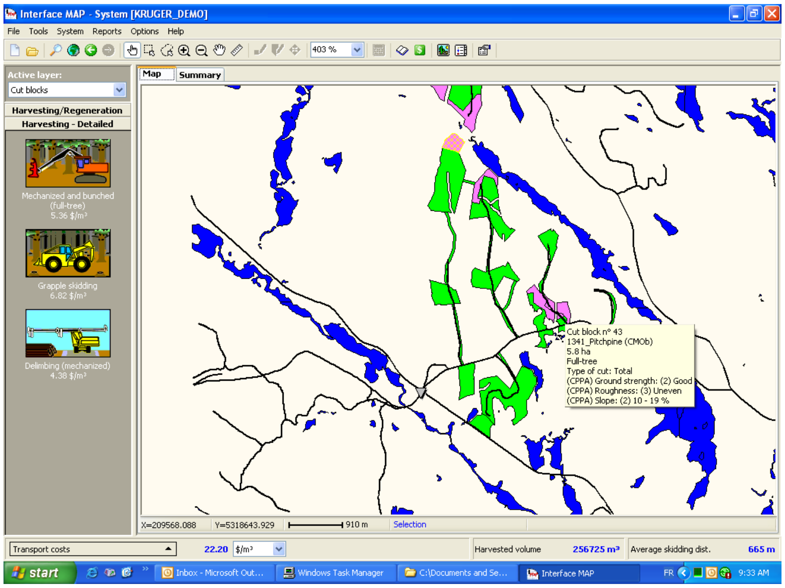

Figure 2. *Interface-Map* screen capture showing cut-blocks, road lay-out and product exit points.

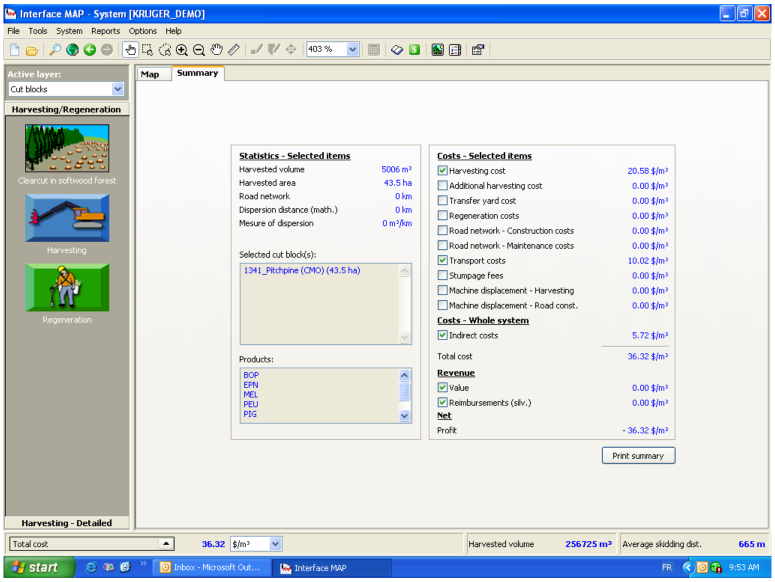

Figure 3. *Interface-Map* screen capture showing summary of cost analysis per product for selected cut blocks.

Interface-Map allows users to allocate the product volumes coming from various blocks to various possible destinations using different routing scenarios and to compare overall delivery costs for these scenarios. In addition, an optimization feature called *MaxTour* has recently been added to this software (Gingras 2005). This module determines haul routes by combining the loads available during a given transportation period and in a given region. This logistics tool minimizes the distances traveled by empty trucks.

Improve recovery

Currently, there is tremendous pressure on the fiber supply in eastern Canada because of a combination of factors, including a reduction in allowable cuts in some jurisdictions, an increase in mill capacity and demand, and increasing amounts of productive land being withdrawn from fiber production for alternative uses. Ironically, the opposite situation prevails in western Canada, where large volumes of timber from stands damaged by the pine beetle are flooding the market.
This fiber shortage is forcing companies to invest considerable energy in maximizing fiber recovery from every harvested hectare and minimizing any waste. FERIC is actively cooperating with the forest industry to develop techniques for recovering additional fiber from harvesting operations.

In addition to efforts to increase fiber volumes, efforts are being made to enhance value recovery during harvesting to reduce the financial impact of decreases in the available volumes. Bucking decisions, for example, can dramatically affect grade and value recovery in both softwoods and hardwoods. To improve bucking practices, FERIC has produced a guide targeted at the owners and operators of cut-to-length machines to help them decrease the variation in log lengths and more easily meet the required log specifications. Produced in Flash, this downloadable tool consists of a 15-minute self-running presentation that covers the following topics:

- Definitions.
- Factors affecting length- and diameter-measurement accuracy.
- Maintenance tips to ensure high accuracy consistently.
- Verifying actual log dimensions.
- The calibration process.
- Setting log-length targets and parameters.

Today's cut-to-length heads do more than measure lengths and diameters. They have become sophisticated merchandizing devices with advanced stem-shape predictors and bucking optimizers. These systems show great potential for improving both volume and value recovery. Sondell (1995) and Sondell *et al.* (2002) provided good reviews of the bucking-optimization systems provided by mainstream harvesters. In a recent FERIC–Forintek study, Corneau *et al.* (2005) compared the value gains from optimized bucking of softwoods using a cut-to-length harvester computer with that of a full 3-D scan on a sawmill's infeed deck. Although the sawmill system provided the optimal bucking solutions, the 2-D predictions provided by the harvester optimizers improved value recovery at a much lower cost than the major investment required for inline scanning at sawmills. The net savings represented CAD $1.40/m^3 compared with the investment in optimization at the mill.

In hardwoods, improper bucking decisions have a much greater financial impact than in softwoods because of the tremendous difference in value between low and high log quality classes. With this in mind, FERIC has actively cooperated with Michigan Technological University in the development of training software called *HW Buck* that helps operators to improve their bucking of hardwoods (Pickens *et al.* 1993). This *Windows* software permits a variety of customizations to suit local conditions, log rules, log grades, and market prices (Figure 4). In field trials, FERIC found that value recovery losses originating from poor bucking patterns could reach 40% of the full potential value (Hamilton 2006).

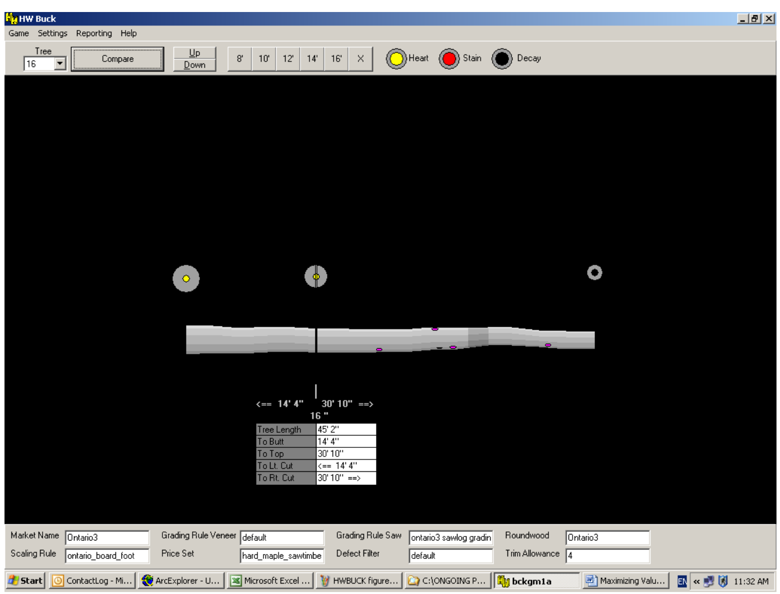

Figure 4. Screen capture of the *HW Buck* software, showing a tree-length stem and a schematic of stem defects.

Decrease value losses due to storage

Efforts made to minimize quality losses can be erased quickly by prolonged or improper storage of wood in the forest or at the mill. Although more and more mills try to balance fiber deliveries with mill consumption in order to reduce inventories, hauling is not feasible in many areas because of adverse weather or load-restriction periods during the spring thaw. In addition, the increasing frequency of forest fires and insect infestations creates surges of salvage volume that often exceed a mill's capacity. Therefore, large wood inventories remain a reality for many forestry operations.

To minimize the decrease in wood quality that occurs during storage and its effects on costs, FERIC has developed a decision-support model called *Opti-Stock*. The objective of this tool is to help managers determine the optimal storage duration under their specific operating conditions. Using information obtained from field studies and published literature, this spreadsheet-based model accounts for the interactions among several variables to predict the cost associated with variations in wood storage duration (Favreau 2001). Figure 5 illustrates the main components of the model, as well as a total cost that integrates all the parameters as a function of storage duration.

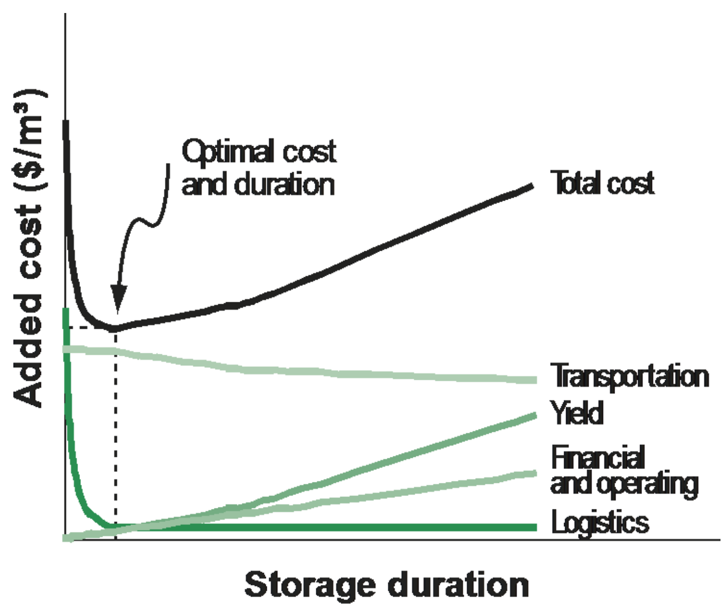

Figure 5. Changes in different cost categories as a function of storage duration during the summer.

The *Opti-Stock* model groups costs into four categories that respond differently to storage duration. Logistics represents the cost to ensure a steady flow of wood to the mill (i.e., having sufficient harvesting and transportation capacity). This cost increases rapidly as storage time approaches zero because of the tremendous capacity that must be added to prevent the risk of any wood shortages. Financial and operating costs increase linearly with storage duration and include pulp bleaching, inventory, insurance, treatment of mill effluents, and mill energy consumption. Product yield costs increase with storage duration because process yield decreases with increasing fiber dryness, and these costs include fiber loss during debarking, lumber yield, and pulp yield. Transportation costs are the only ones that diminish with increasing storage duration because less water is hauled as wood dries. The four individual cost components are combined to produce a total cost curve whose minimum cost value identifies the optimal storage period, and the graph shows the evolution of total costs over time.

Inevitably, some wood storage is required in most forestry operations. From a quality perspective, every effort must be made to prevent the quality degrades that result from this storage, mainly as a result of moisture loss, fungal staining, and (at more advanced stages) checking, rot, and insect attack. Gingras and Sotomayor (1992) discussed the variation in moisture of standing, felled, and stored softwood logs and stems as a function of storage duration and examines various storage implications One protection strategy that has been around for centuries but that has been only recently applied to roundwood is storage under snow. Pioneered in Finland, the technique has now been tested and implemented operationally in several eastern Canadian operations with the assistance of FERIC (Nader 2003). The technique involves burying large volumes of roundwood under snow during the winter months and covering this snow with an insulating layer that typically comprises organic material such as bark, sawdust, or debris. These piles are then opened in mid- to late summer as fresh wood is required. Figure 6 illustrates the March and August temperature differences between a control pile and a pile stored under snow in one FERIC trial.

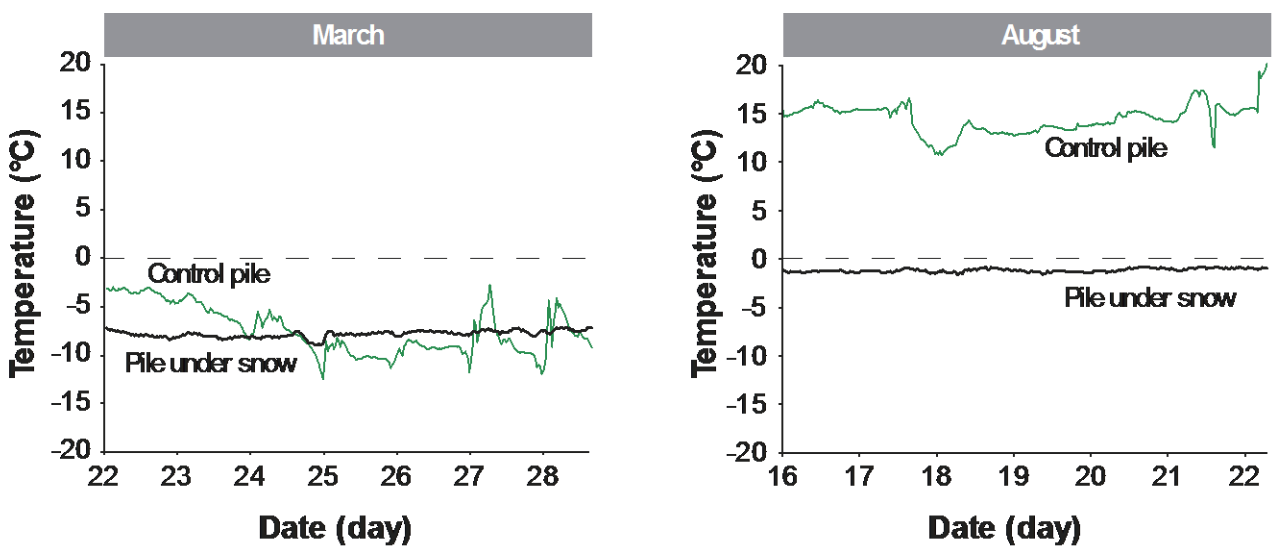

Figure 6. Temperature difference in piles stored under snow and control piles.

The snow-covered piles in this test systematically remained at or below 0°C This greatly reduces the risk of discoloration of the stored wood and attack by insects. In fact, the moisture content of wood stored under snow actually increased as a result of snowmelt during the summer. Nader (2005) found that storage under snow is thus a relatively inexpensive alternative to the use of sprinklers and other water-based storage techniques.

2. CONCLUSION

Managing operations by means of the RAID concept ensures that best practices are used to deliver the highest-quality raw material to the client. Reducing breakage and damage to logs, allocating the right log to the right mill, improving volume and value recovery, and decreasing value losses due to storage are all key strategies for maximizing the quality of the fiber delivered from harvest operations.

We have seen that a combination of best operating practices and the right equipment can minimize breakage and damage levels, even in full-tree to roadside logging systems. Also, optimized log allocation will increasingly prove to be an important operational parameter in eastern Canadian operations. In this context, appropriate advance planning using software such as *Interface-Map* and tools such as onboard computers in harvesting machines will help to optimize product merchandizing and sorting and will help to establish appropriate delivery schedules. Improving both volume and value recovery through optimized merchandizing is key to improving the financial situation of the forest industry. Finally, we discussed how tools such as *Opti-Stock* and techniques like storage under snow can reduce the risk of quality downgrades as a result of wood storage.

Company managers should review their chain of operations in light of the RAID concept to optimize all phases of their operations and avoid jeopardizing wood quality in any phase. FERIC has produced decision-support information and tools to assist company managers in this assessment.

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The Realities of Forest Work Mechanization and Skilled Workmen Training and Their Practical Use in Korea*

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Abstract
In the 1950s forestry machines were first used in Korea. Since then, various forestry machines have been introduced and utilized in training centers and forest management fields. Since the 1990s various domestic small machines have been developed and generalized in Korea. Currently Korea is in the stage of semi- mechanization. In a general timber harvesting system, chain saws are used for tree felling and bucking; and grapples attached to excavators, plastic chutes, small winches and skidders are used for bunching and hauling. For timber hauling in forestlands, small hauling vehicles like forwarders and dump trucks are used. Research related to forestry mechanization has been performed in the Laboratory of Forest Mechanization in the Korea Forest Research Institute. Six Forest Machine Support Centers of the National Forestry Cooperatives Federation (NFCF) are in charge of leasing high valued and functional forestry machines. Three Forest Work Training Centers of the NFCF are responsible for training forestry machine operators and timber harvesting workers. The Korea Forest Service has established a mid- and a long-term project for the cultivation of forest craft workers. The project aims to train 10,000 forest skilled workers in 850 work units by 2007.

Key words: semi-mechanization, forest machine support center, forest work training center

1. INTRODUCTION

In Korea, circumstances governing timber imports are predicted to turn bad and the demand of wood produced domestically may continually increase. However, wood prices in Korea for the past 2 decades have remained the same while workers' wages have increased dramatically. Consequently, the economical efficiency of wood production has decreased in Korea (Korea Forest Service, 1999). In addition, manpower shortages are getting worse because the population in rural communities is decreasing and rapidly aging for forest labor like forestation, forest tending , and logging. More over, many people avoid forest labor, which is considered to be representative of primary industry and to demand harder physical labor. Forest work mechanization is essential to secure economical efficiency in timber harvesting and to solve both problems of manpower shortage and work safety.

There are many obstacles for forestry mechanization in Korean forest conditions. First of all, more than 60 % of Korea's forests are in the rugged highlands with slope angles over 30

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 495-502.*

degrees. Only restricted private forest managers can afford machines and equipment because of high prices. Even in national forests, forest work mechanization is limited to the situations where a certain amount of work is ensured for economical efficiency. The severe shortage of skilled workmen is getting worse because the employment for forest work is not secured (Korea Forest Service, 1999).

This study analyzed what kinds of machines and equipments are held in Korea, how much forest work is mechanized, how well the institutes and programs are applied to train operators and skilled men for forest mechanization, and how practically the trained manpower is in use.

2. METHOD

Based on the statistical data from the Korea Forest Service and related forestry organizations, this study analyzed the development process of forest work mechanization in Korea; the machines and equipments held; the institutes and organizations related to forest work mechanization; the training centers and programs to train operators and skilled workmen for forest work mechanization; and the practical use of the trained manpower. To analyze the extent of forest work mechanization, forest workmen were interviewed during the period of timber harvesting and field studies were performed.

3. RESULTS AND DISCUSSIONS

3. 1 Forest Machines Held

1) The process summary of forest work mechanization in Korea

The first introduction of machines for forest work into Korea was made in the 1950s when U.S. Army 6WD GMC trucks were used to carry logs from the highlands to lumber mills and U.S. Army chain saws were used in nonmilitary areas. In 1969, Japanese chain saws (Rabbit), bush cutters (Robin), earth augers (Robin), bulldozers (Komatsu, 4D-120) were introduced into national forests and a middle sized yarder (Iwafuji, Y-28D) was used on a trial basis. In the 1970s, chain saws were widely used, and replacing saws and axes in felling works.

In the 1980s as a part of the Korea and Germany Forest Management Program, German chain saws, bush cutters, and sapling nurturing and forest-tending equipment were introduced for training. In 1985, Austrian mobile tower yarders (Koller, K-300) and German Werner winches topped on multipurpose tractors (Mercedes-Benz, MB-trac 900) were introduced. Also, Austrian plastic chutes and yarders attached to tractors (Holzknecht, Logging Bogies) and English tractor-mounted tower yarders (Timber Master) were introduced (Korea Forest Service, 1999).

In the early of 1990s, Japanese middle sized yarders (Iwafuji, Y-28DE) and radi-carry (Iwafuji, BCR 08SP) were used in private forest works. In 1992, the Korea Forest Service introduced into national forests Austrian trailer-mounted tower yarders (Hinteregger, Urus I) and winches attached to farm tractors (Korea Forest Service, 1999).

From the middle of the 1990s, the Laboratory of the Forest Mechanization in Korea Forest Research Institute started to research and develop Korean forest machines. The lab developed winches with tractor, plastic chutes, remote controlled winches, and multipurpose hauling vehicles. Also, other private industries developed and generalized tractor-attached tower yarders (HAM 200), a winches with excavators, tractor-attached remote controlled winches, and log hauling and transportation vehicles (Korea Forest Service, 1999). So far, 24 kinds of forest work machines have been developed and generalized.

2) The spread of forest work machines

The sapling nurturing, forest tending, and timber harvesting machines and equipments generalized in Korea are shown in Table 1. From 1998 to 2004, the number of sapling nurturing machines and timber harvesting machines increased while that of forest tending machines decreased. The total number of forest machines also decreased. In 2004, the numbers of timber harvesting machines, forest tending machines, and sapling nurturing machines were 8,637; 6,026; and 598, respectively. When the kinds of machinery are considered, the number of chain saws (5,631) is the highest with bush cutters (2,445), chutes (2,238), saws for high branch cutting (1,733), small winches (316) and earth augers (202) following. Since logging dealers and farmers have many chain saws and bush cutters, the actual numbers would be bigger than the statistical ones.

These machines are generalized mainly in public organizations such as the Korea Forest Service (KFS) (16.0%), cities/provinces (34.5%), and Forestry Cooperatives (FC) (49.5%). FC has the most number of forest tending machines, with cities/provinces and KFS following. FC also has the largest number of timber harvesting machines. Most timber harvesting machines are small machines such as chain saws, chutes, small winches. Only FC owns some other machines like skidders and hauling excavators. Some machinery like crawler hauling vehicles, loaders, and aerial cable ways were held in 1998, no longer according to the statistical data in 2004.

Since forest works demands more mechanization in Korea, the training centers,Forest Training Center (FTC) and Forest Works Training Center (FWTC), hold high functional forest machinery like tower-yarders, processors, and mini forwarders, and they apply them in their training programs, demonstration projects, and adaptability. A small number of harvesters and mid-big sized hauling vehicles were imported in 2005 for training programs and demonstration projects.

3.2 Forest Work Mechanization

1) Forestation and forest tending works

Tree planting in Korea has been rarely mechanized and characterized by physical labors. They would use chain saws, bush cutters and machetes to prepare the sites and then plant trees in a traditional way. About 87.4 % of forest area in Korea has trees under 40 years old (Age Class I: 5.7%, II: 15.1%, III: 38.4%, IV: 28.2%, V~VI: 10.1%) and the forest tending works are critical for the present and the future (Korea Forest Service, 2005). Until now, the forest tending works were limited to cutting herbaceous plants and vines around young saplings for 4-5 years after plantation and to pruning and thinning of larger trees.

For both natural and artificial forests, the forest tending works started in 1998 when 'Forest-Tending Works' by the 'Public Employment Works Projects' was launched. It was one of the IMF's Restructuring Programs and lasted till 2001. During those four years, about 13,000,000 people were employed and 420,677 ha of forest areas were successfully tended. As a part of NGO (National Movement of the Forest For Life (NMFFL)) activities, about 20,000 volunteers from larger cities participated to experience forest tending practices. Later, NMFFL technically monitored the forests tended by the project (Woo, 2002). The forest-tending work was considered to be successful and it is still performed even after the IMF period. Now it includes reforestation, weeding, sapling tending, vine/creeper cutting, thinning and natural forest tending (Table 2).

Table 1. Forest machines and equipments held (Korea Forest Service, 2005).

Year, Agency	1998	2004			
Machinery	Total	Total	KFS	City/Province	NFCF
Total	**27,794**	**23,382**	**3,731**	**8,066**	**11,711**
○ **Sapling nurturing**	**570**	**598**	**147**	**244**	**207**
○ **Forest tending**	**10,697**	**6,026**	**526**	**2,473**	**3,027**
○ **Timber harvesting**	**6,566**	**8,637**	**2,294**	**1,755**	**4,588**
Machine saw	5,136	5,631	1,225	1,518	2,888
Small winch	329	329	68	42	219
Chute	718	2,238	868	186	1,184
Skidder	38	22	11	-	11
Hauling excavator	-	29	15	-	14
Forwarder	7	7	4	-	3
Loader	11	-	-	-	-
Aerial cable way	59	-	-	-	-
Excavator	7	44	23	-	21
Tractor	-	20	10	3	7
Tower-yarder	-	10	4	-	6
Processor	-	11	10	-	1
Skidder	-	1	-	-	1
Radi-carry	-	1	-	-	1
Wood grapple	-	29	24	-	5
Others	259	265	32	6	227

In the forest-tending works, bush cutters, saws and machete are used for weeding, sapling tending and vine cutting; and saws, saws for high branch cutting and chain saws are used for thinning and natural forest tending. Remote controlled auto-pruners are used for thinning on a trial basis in some cypress(Chamaecyparis obtusa) forests. Chain saws are widely used for thinning in artificial and natural forests.

Table 2. Status of Forest-tending works (Korea Forest Service, 2005)

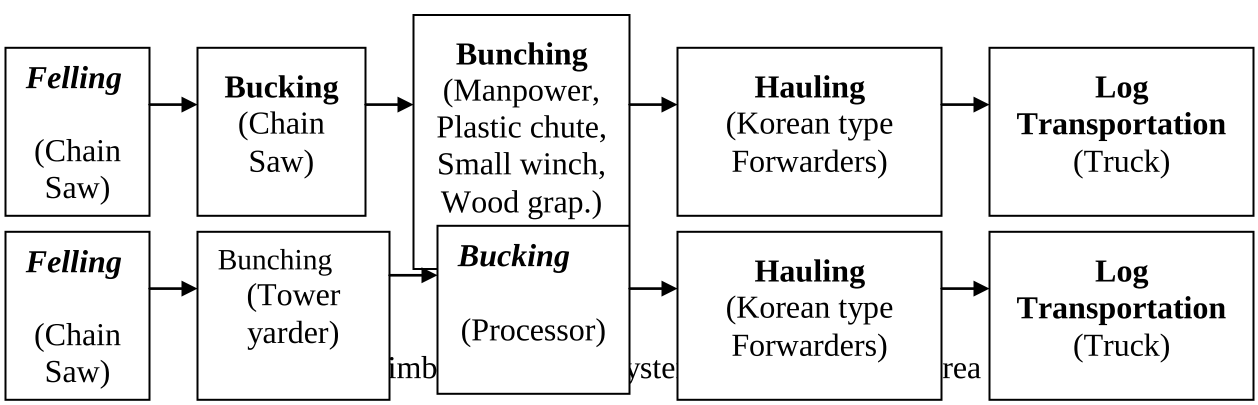
Year	Total	Refores -tation	Weeding	Young sapling tending	Vine cutting	Thinning	Natural forest tending	Others
1998	40,404	-	2,251	3,842	5,996	8,080	14,785	5,090
1999	129,466	2,153	12,076	7,312	21,775	33,730	42,513	9,907
2000	117,097	2,824	10,598	4,886	16,733	32,301	38,258	11,497
2001	133,710	16	57,394	14,959	26,877	17,637	16,827	-
2002	244,768	28	66,481	33,530	54,245	42,035	48,449	-
2003	346,139	51	70,955	38,285	64,451	68,432	103,312	653
2004	336,682	-	64,614	25,702	48,486	68,349	110,838	18,693
Total	1,348,266	5,072	284,369	128,616	238,563	270,564	374,982	45,840

2) Timber harvesting

The logging area per year for final clearing, thinning and tree species conversion in Korea is about 50,000 ha (1,200,000 m^3. The Short Tree Harvesting Method (Felling - Bucking - Bunching - Hauling to forest roads or landing near forest roads) is the most common system in Korea.

Felling and bucking are done with chain saws. In many cases people still manually bunch the logs after bucking, sometimes, plastic chutes and small winches are used for bunching. Bunching by wood grapples attached to the excavator is increasing, but the frequent traveling of excavators has caused severe forest damage and a number of landslides under excavator driveways after a concentrated heavy rain.

In forestlands, Korean type forwarders modified from farm cultivators, and small sized dump trucks make the log hauling to forest roads or landings. In some cases, Tower-yarder Type Harvesting System with tower-yarders and processors has been tried. Many different tower-yarders imported from foreign countries and developed in Korea are used in various work systems (NFCF, 2003). The representative tower-yarders developed and used in Korea are HAM200 and HAM300. Normal 5-15 ton goods trucks are used to transport logs to marketplaces.



3.3 Institutes and Training Programs Related to Forest Work Mechanization

1) Institutes related to forest work mechanization

The Laboratory of Forest Mechanization of Forest Practice Research Center in the Korea Forest Research Institute has performed researches for forest work mechanization. In the lab, there are three researchers who are involved with the development of forest work machines and systems. The Forest Training Center of NFCF trains the operators of high functional forest machines and equipments. The center was established as a part of the Korea and Germany Forest Management Program in 1982. Since then, the center has performed skilled forest workman training. Other organizations that train forest workmen include the FWTC and TESC in the NFCF (Fig. 2).

Six regional Forest Machine Support Centers of NFCF are in charge of high valued machine leases (Fig. 2). The center, along with 3 training centers and 3 regional FC, is under the NFCF. There are administrators, trainers, operators and chockers working for the center (Table 3). Since most of chockers are hired on a daily basis when they are needed, there are many problems including lower work efficiency, frequent machine breakdowns, and damages to remained trees in thinning. Because logging schedules are usually overlapped and concentrated to a certain season, machine and operator supply cannot meet the demand. Thus, more machines, trainers and operators are wanted, and chockers need to be employed on a regular basis.

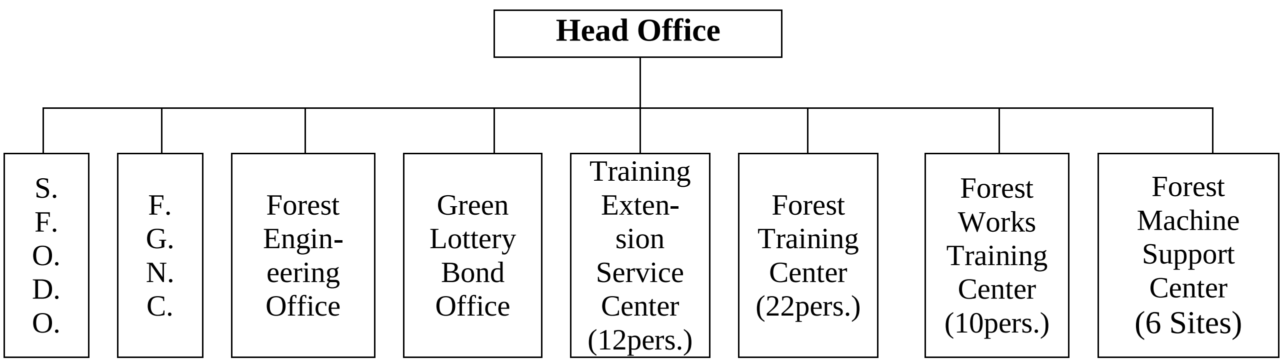


Fig. 2. Organization of the National Forestry Cooperatives Federation

Table 3. Manpower and Machines of Forest Machine Support Center (NFCF, 2006)

Center	Manpower				Main machines for lease					
	Total	Manager/ Instructor	Operator	Chocker	Total	Tower yarder	Wood grapple	Mini Forwarder	Winch	Truck
Central F.M.S.C	7	3	2	2	4	1	2			1
Western F.M.S.C	4	2	2	(8)	9	2	1	1	4	1
Southern F.M.S.C	4	2	2	-	6	2	1		2	1
Cheongju F.M.S.C	4	2	2	(2)	16	2	2		9	3
Sooncheon F.M.S.C	4	2	2	(5)	6	2	1		1	2
Pyeongchang F.M.S.C	4	2	2	-	6	1	2		1	2
Total	27	13	12	2(15)	47	10	9	1	17	10

2) The training program operation to train skilled workmen

The Forest Training Center (FTC) has training programs mainly for machine operators. The programs last 3 weeks and the main subjects are Internal Combustion, Operation of Bunching and Hauling Machinery, Harvesting Methods, Tractor Bunching, Forwarder Drive, and Tower yarder Drive. Current programs do not include operation training of high functional machines like Harvesters and Processors. This part needs to be included in the programs. Present operator training programs are focused on work efficiency promotion, production price reduction, and work safety. Training programs need to aim to secure higher forest production, damage reduction, and ecologically sustainable forest works through improvement of forest work quality. The center also runs timber harvesting related training programs such as a Primary Instructor Class (1 wk), Intermediate Instructor Class (1 wk), Primary Training for Units of Forest Craft Workers (3 wks), Complementary Training for Units of Forest Craft Workers (1 wk) and Forest-tending Techniques (2 wk) (Korea Forest Service, 2003).

The major curriculum of FWTC and Training Extension Service Center (TESC) includes primary practical skills such as Reforestation, Forest-tending, Timber harvesting and Stonework; and regular techniques for small machine operation of chain saws, bush cutters, small winches, and chutes. These centers also have training programs for forestry management engineers and forest soil engineers.

3.4 Cultivation and Practical Use of Forest Craft Workers

The Korean government established the 'Mid- & Long-Term Training Project for Forest Craft Workers' in 1995 to train workers systematically and efficiently. The scheme of the project is to expand the bases of education, training and welfare for forest workers, to organize continually and to activate the units of forest craft workers.

According to the project, 10,000 forest skilled workers will be trained and 850 units of forest craft workers will be organized until 2007. There were 7,675 forest craft workers are in 722 units (1,833 workers in 137 units for National Forests, 5,842 workers in 585 units for Private Forests and Civil Corporation) organized 2005. In 2006, 30 units (360 workers) will be organized for private forests (Table 4).

One of the primary administrative aims of the units of forest craft workers is to secure regular income for the unit workers. Another is to improve forest administration laws, to divide forest works equally for the whole year, and to study and find better ways for industrial disaster insurance and welfare for the unit workers. Since 2001, there has been an annual competition of skilled forest workers to keep their skills and spirits high. Those who get higher scores in the competition are granted incentives so that they can visit and study in foreign countries.

Table 4. Cultivation plan of forest craft workers and unit of them (Korea Forest Service, 2006)

	Goal	2005	2006 ~ 2007
Total	10,000 workers (850 units)	7,675 workers (722 units)	2,325 workers (128 units)
Units of forest craft workers for national forests	2,743 workers (232 units)	1,833 workers (137 units)	910 workers (95 units)
Units of forest craft workers for private forests & civil corporation	7,257 workers (618 units)	5,842 workers (585 units)	1,415 workers (33 units)

3.5 Development Scheme of Forest Work Mechanization in Korea

To promote the development of forest work mechanization in Korea, the forest management base of forest roads and work lanes needs to be strongly constructed. Practical machines and working systems for Korea need to be developed. The operating ratio of forest machines could be improved by thinning expansion. Forest worker training is essential. Financial assistance or loan services would promote the introduction of better forest work machines. The system for logging dealers can be put in to better order, and regional main bodies for timber harvesting need to be established. Environmentally friendly techniques for timber harvesting can be improved by strengthening related laws. The lease of high valued machines needs to be expanded. Running mechanized model sites for forest works can be a way to activate the development of forest work mechanization. Above all, continuous training and education, technique improvement, and systematic wages and welfare for workers are points to be considered in the long run.

4. CONCLUSION

The first machines and equipments for forest works were introduced in Korea in the 1950s. Until the 1990s, various machines and equipments were imported from foreign countries and used in forest management fields, and education and training centers. Since the 1990s mainly small machines and equipments have been developed domestically and generalized in Korea.

The mechanization of forest works in Korea has been made mainly in forest tending and timber harvesting. Manual saws for high branch cutting are used for pruning in forest tending and remote controlled auto-pruners are used in *Chamaecyparis obtusa* stands on a trial basis. In forest tending works, chain saws are mainly used for thinning.

Forest harvesting is in the stage of semi-mechanization at present. Chain saws are used for felling and bucking, and wood grapples attached to excavator, plastic chutes, small winches and tractor-mounted yarders are utilized for bunching, skidding and yarding. Rebuilt Korean type mini-forwarders and small dump trucks are used for hauling in forest lands, and goods trucks (5-15 ton) are utilized for log transportation.

The Laboratory of Forest Mechanization in the Korea Forest Research Institute has worked to improve forestry mechanization. Six Forest Machine Support Centers in the National Forestry Cooperatives Federation (NFCF) are in charge of the lease of high valued and functional forestry machines.

The Forest Training Center of NFCF is for training forest craft workers operating timber harvesting machines and equipments. Forest Works Training Center and Training Extension Service Center of NFCF are for training other forest workers. The major curriculum of FWTC and TESC includes primary practical skills and regular techniques for small machines. The centers also have training programs for forestry management engineers and forest soil engineers.

Since current quantity and quality of forest workers is insufficient in Korea, Korea Forest Service has a mid- and long-term project for the cultivation of forest craft workers. The project aims to train 10000 forest skilled workers and organize 850 units of forest craft workers by 2007.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Safety Training for Hispanic Logging Workers in the Southeastern United States*

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Abstract
Hispanic (Spanish-speaking) workers make up a significant and increasing segment of the logging industry workforce in the Southeastern United States. While the overall logging injury rate in the U.S. has decreased over the past 10 years, the fatality rate for logging remains excessively high, justifying logging's rank as the country's most hazardous occupation. At the same time, recent injury rates in the construction and agriculture industries have been found to be significantly higher for Hispanic workers than for non-Hispanic workers. Some safety experts believe this is likely a result of ineffective safety training due to language difficulties. Thus, this study was undertaken to assess the status of safety training currently being provided to Hispanic workers in the logging industry in the Southeastern U.S. Study objectives were (1) to determine the current percentage of Hispanic workers in the region's logging workforce, and (2) to determine the safety training presently being provided to these workers. Study methods included surveying nearly 2000 logging operations across the South, and conducting in-depth interviews with 40 loggers who employ Hispanic workers.

1. INTRODUCTION

Hispanics are becoming an increasing part of the U.S. private industry labor force, with approximately 17.5 million Hispanics in the workforce as of the end of 2004 (DOL 2004). In 2003, foreign-born workers made up about 14 percent of the U.S. civilian labor force age 16 and over, and of that 14 percent, 48 percent were Hispanic or Latino (BLS (2) 2004). They fill many low-skilled jobs that Americans cannot or do not want to perform (Krikorian 2004). Hispanics (non-college educated) in the U.S. labor force primarily enter the country as seasonal migrant workers (guestworkers) through labor contractors, and work under either an H2A or H2B visa. There are also a large number of Hispanics who are working in the U.S. as illegal immigrants.

A report released by the Pew Hispanic Center concludes that for nearly a century now the U.S. has relied on Mexican migrant workers to fill domestic labor shortages in nearly every area of U.S. commerce (Lowel and Suro 2002). The sectors that Spanish-speaking workers (SSWs) tend to fill usually involve labor-intensive/low paying work and are related to the agriculture or construction industry (DOL 2004). In the farming, fishing, and forestry occupations alone, almost one in every three employed were Mexicans (Grieco and Ray 2004).

The safety of SSWs is becoming a concern due to their high numbers in U.S. private industry. The number of fatal work injuries involving Hispanics or Latino workers was on a steady rise from 1995-2002 (BLS (2) 2003). Although fatalities were lower for Hispanic

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* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 503-512.*

workers for the first time in seven years in 2002, they still experience a slightly disproportionate share of work related deaths, injuries, and illnesses (DOL 2004). In 2000 and 2001, deaths among Hispanic workers were rising by 12% and 10%, respectively, while overall workplace fatalities were falling (DOL 2004). This is especially evident in the construction industry where Hispanic workers represent about 18% of the workforce while accounting for 21% of deaths on the job (DOL 2004). In 2003 Hispanic or Latino workers accounted for 14% of the total fatal occupational injuries (BLS 2003). This trend can also be seen in nonfatal injuries. In 2002, Hispanics made up 10.9% of the private industry work force, yet they accounted for 12.5% of the nonfatal injuries or illnesses that involved days away from work (EEOC (1) 2002, BLS 2004). This can be compared to blacks, the largest minority group in private industry, who accounted for 13.9 of the private industry work force and only 8% of the nonfatal injuries or illnesses that involved days away from work (EEOC (2) 2002, BLS 2004).

Recently, many professionals whose work routinely brings them in contact with logging operations in the Southeastern U.S. have reported observing a dramatic increase in the number of Hispanics being employed throughout the region's logging businesses (Shaffer 2004). An increase in the number of Hispanics in the southern logging industry brings concern because of the danger and safety issues that coincide with the industry. In 1996 logging was the second most dangerous occupation in the U.S. (FRA 2002). From 1996 to 1998, 321 loggers died in the U.S. from injuries received in a job-related accident – the highest fatality rate for any industry during that period (FRA 1999). In the 1996-1997 fiscal year the southern forest region accounted for 49% of the OSHA-investigated logging fatalities (FRA 2002). In 1996 the U.S. Bureau of Labor Statistics reported an injury rate of 8.7 per 100 workers per year in the logging industry, while in 2001 the rate was 6.4 injuries per 100 workers per year (FRA 2000). In mechanized logging operations in the U.S. South, injury rates have decreased from 10 injuries per 100 workers per year in 1996 to 4.9 in 2003 (Roberts and Shaffer 2004). Yet, even with the recent reductions in injury rates logging workers still have a fatality rate of 131.6 per 100,000 employed, more than five time that of a construction laborer (BLS (2) 2003).

Industry experts agree that the recent reduction of logging injuries has been primarily due to: (a) reduced exposure to manual chainsaw delimbing as more loggers purchase and use mechanical delimbing devices, and (b) increased industry-wide emphasis on logging safety training (Shaffer and Roberts 2001). To keep reduced fatalities and injuries in the logging industry it is important that safety training be continued, or expanded, in a manner and form that will effectively reach all logging employees, including those whose primary language is Spanish.

In response to the aforementioned concerns, this study was undertaken to assess the status of safety training currently being provided to Hispanic workers in the logging industry in the Southeastern U.S. The study objectives were (1) to determine the current percentage of Hispanic workers in the region's logging workforce, and (2) to determine the safety training presently being provided to these workers.

2. METHODS

The study area for this project is the Southeastern United States. This is an area that starts at Virginia and, moving southwest, ranges as far south as the Gulf Coast and as far west as Oklahoma and Texas.

Data for the study was collected through two methods. The first set of data was collected through on-site surveys performed by three of the largest WCI providers for the logging industry in the Southeastern U.S. The participating WCI carriers were Davis-Garvin, Inc. of Columbia, SC, Amerisafe Inc. of Baton Rouge, LA, and Forestry Mutual of Raleigh, NC. Field agents for the three WCI carriers conducted the surveys of their insured logging operations within the study area during the summer of 2005. The surveys took place during the field agent's routine safety inspection visits to the logging operations which they perform year-round. The surveys recorded three observations for each logging crew visited: (1) the state and geographic region of the operation, (2) the total number of employees on the logging crew, and (3) the total number of Hispanics (Spanish speaking) on the logging crew.

The second data set for this study comes from interview questionnaires completed by selected sample logging operations that are currently employing one or more SSWs. Sample logging operations were purposely selected from a representative group of logging business owners who employ Hispanics. This task was carried out by Virginia Tech researchers and project cooperators who identified logging business owners employing Hispanics, and conducted interviews with them or provided the business owners with the questionnaire through correspondence. All questionnaires were completed during late summer and early fall of 2005. The questionnaire collected information regarding the current methods of safety training for Hispanics, as well as the respondents opinions of the most effective methods.

3. RESULTS

3.1 Survey

There were 1890 logging operations surveyed for this study. These crews collectively employed 11,525 total employees, of which 388 were identified as Spanish-speaking (Table 1). Thus, Hispanics represent 3.37% of the logging workforce in the study area.

Table 1. Survey results by region and state.

REGION	STATE	CREWS	EMPLOYEES	HISPANICS
Atlantic	Virginia	136	666	21
	North Carolina	291	1386	97
	South Carolina	89	620	7
	Tennessee	101	546	0
Eastern Gulf	Georgia	281	1508	19
	Florida	11	47	10
	Alabama	169	901	6
	Mississippi	151	953	10
Western Gulf	Louisianna	163	1368	0
	Arkansas	400	2720	185
	Oklahoma	44	452	18
	Texas	54	358	15
TOTAL	**Southeastern U.S**	**1890**	**11525**	**388**

The total employee sample size was compared to the estimated total logging employee workforce in the study area of 34,507 (BLS 2004c), providing a sample of 33.4% of the total population (Table 4). Taking into account the large sample size and using a confidence level of 99%, this data produces a confidence interval of < 0.35 for the percentage of Hispanics in the Southeastern logging workforce. According to Bureau of Labor Statistics population data we can be 99% confident that the percentage of Hispanics in the Southeastern logging workforce falls between 3.05% and 3.75%. Thus, the current population of SSWs in the Southeastern logging industry is 1162, ranging between 1051 and 1293 workers.

Of the 1890 operations surveyed, 192 of them employed one or more Hispanic. This represents approximately 10% (10.16%) of the sample crews, which is a significantly higher statistic than the Hispanic population percentage in the Southeastern logging industry (3.37%) (Table 2). This data also reveals that of the 192 crews with 1 or more SSW, the average number of SSWs per crew is 2.02.

Table 2. Demographic statistics by sub-region.

REGION	CREWS	PERSONNEL	HISPANICS	%	CREWS W/HISPANICS	%
Western Gulf	661	4898	218	4.45%	108	16.34%
Eastern Gulf	612	3409	45	1.32%	22	3.59%
Atlantic	617	3218	125	3.88%	62	10.05%
TOTAL	**1890**	**11525**	**388**	**3.37%**	**192**	**10.16%**

3.2 Questionnaire

A total of 41 questionnaires were collected from logging crews in eight Southern states. The total number of employees working for the sample logging business owners (respondents) was 582, with 179 of them Spanish-speaking. The average respondent employed 14 workers of which four (29%) were Spanish-speaking. The median respondent employed ten workers of which two (20%) were Spanish-speaking. The average respondent had employed for 6.7 years, while the range was from less than 1 year to 20 years. The median employment time for Hispanics was six years. More than one-half (63%) of the Hispanics on these crews had previous logging experience before entering their current job. Of all respondents, four (10%) did not provide their Hispanic workers with safety training, and 44% had Hispanics injured on the job.

Respondents were asked to rate different methods of safety training on their effectiveness for training Hispanics (Figures 1-6). Using "hands-on" demonstration training, where the worker observes a safe operating practice and then tries it himself, was considered the most effective way to train Hispanics by 73% of the respondents (Figure 1). This was also the only method that no respondents believed would definitely not be effective. Showing American-made safety videos with Spanish subtitles appearing at the bottom of the screen was considered the least effective way to train Hispanics, with only 8% of the respondents believing it was definitely effective (Figure 2). This method also had the highest percentage of respondents (13%) believing it was definitely not effective. Using a bi-lingual SSW to interpret a tailgate safety meeting at the landing and attending local safety training programs presented by a Spanish-speaking safety instructor were the next two most effective methods of training Hispanics, with

59% and 54% of respondents, respectively, believing they would be definitely effective methods (Figures 3&4). The last two suggested methods, using safety brochures and manuals printed in Spanish and using pictures and diagrams rather than text in safety brochures, were not believed to be highly effective, with only 43% and 33% of the respondents, respectively, believing them to be definitely effective (Figures 5&6).

When looking at the potential effectiveness of each training method (definitely effective + probably effective) the results are similar. The order of greatest to least potentially effective training method is as follows (along with the percentages of respondents classifying the method as definitely effective or probably effective);

1. (97%) Using "hands-on" demonstration training where the worker observes a safe operating practice and then tries it himself.
2. (87%) Using a bi-lingual Hispanic to interpret a "tailgate" safety at the landing to his co-workers.
3. (87%) Attending local safety training programs presented by a Spanish-speaking safety instructor.
4. (85%) Using safety brochures and manuals printed in Spanish.
5. (76%) Using pictures and diagrams rather than text in safety brochures.
6. (56%) Showing American-made safety videos with Spanish subtitles.

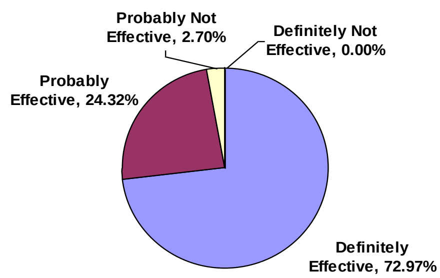

Figure 1. Effectiveness of using "hands-on" demonstration training where the worker observes a safe operating practice and then tries it himself.

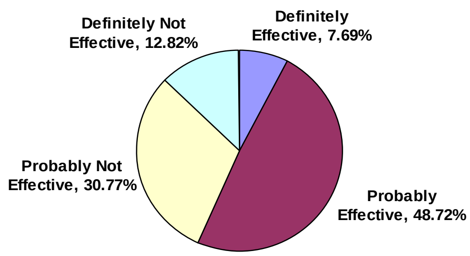

Figure 2. Effectiveness of showing American-made safety videos with Spanish subtitles appearing at the bottom of the screen.

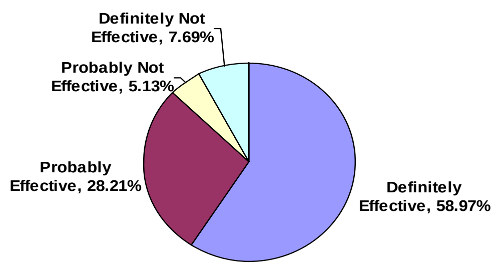

Figure 3. Effectiveness of using a bi-lingual Hispanic worker to interpret a "tailgate" safety at the landing meeting to his co-workers.

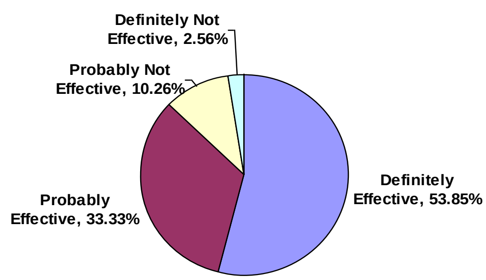

Figure 4. Effectiveness of attending local safety training programs presented by a Spanish-speaking safety instructor.

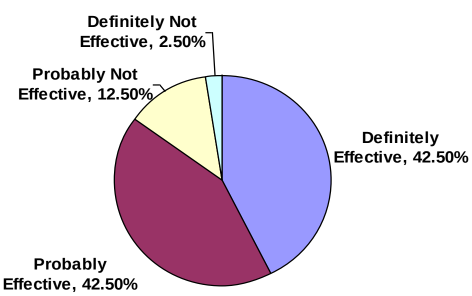

Figure 5. Effectiveness of using safety brochures and manuals printed in Spanish.

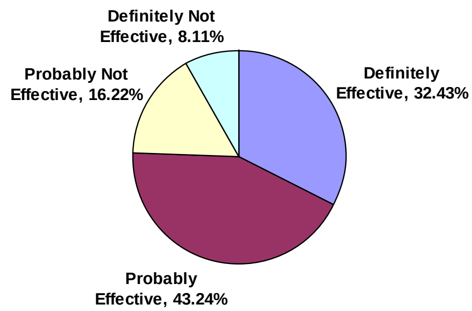

Figure 6. Effectiveness of using pictures and diagrams rather than text in safety brochures.

A brief explanation was given by the respondents who provide safety training for their Hispanic workers describing the safety training method(s) they are currently using.

Few respondents used more than one method such as holding monthly "tailgate" safety meetings and using an interpreter, while most respondents only used one method of safety training such as only having safety meetings or sending their Hispanic workers to formal logger training programs. The following is a break-down of the different kinds of training provided by the respondents for their Hispanic workers;

- 23% use only hands-on/demonstration type training
- 14.5% use only safety meetings
- 14.5% only talk about safety in a general sense or when needed
- 12% use only an employee or hired translator/interpreter
- 12% use only third party training programs (SFI, SHARP, Insurance Co.)
- 9% use only Spanish materials
- 3% use only safety brochures with pictures
- 12% use a combination of the previously listed methods

4. DISCUSSION

4.1 Survey

Reasons for the relatively low population of Hispanics in the logging industry may be explained by two factors. First, professionals who are regularly in contact with logging operations in the Southeast have noticed an increase in the number of Hispanics on logging crews only in the past few years (Shaffer pers com 2004). This coincides with questionnaire data that shows 49% of the respondents have employed their Hispanic workers for 5 years or less. Thus, the number of Hispanics has only recently begun to rise to considerable numbers, but overall it is still relatively low.

The second factor may be attributed to the H2B visa cap. Presently, the maximum amount of H2B visas that can be issued is 66,000. Recently, this number has been reached early in the fiscal year, leaving many employers without the much needed immigrants to fill manual labor jobs in the non-agricultural work sector (Murphy 2004). Since (Spanish-speaking) immigrants in the logging industry can only work legally under an H2B visa, this may be a limiting factor to the number of Hispanic workers that can be acquired to fill the needs of the industry.

These factors lead to 3 conclusions about the population of Hispanics in the Southeastern U.S. logging industry: (1) Only recently has the population of Hispanics begun to accumulate in high enough numbers to make them a substantial labor source for the logging industry, (2) The H2B visa is potentially an influential factor in limiting the number of Hispanics in the industry, and (3) The current population has the potential to increase in the future, more-so if the H2B visa cap is removed or expanded.

A critical statistic regarding the Hispanic population is the percentage of all operations with one or more Hispanic. Ten percent of the surveyed crews employed a Hispanic. These crews are all subject to dealing with the necessity of providing effective safety training to account for the language barriers between employers and employees, even if they only employ one Hispanic. This percentage is over three times greater than the entire Hispanic workforce percentage, and shows that there are few logging crews that are predominantly Hispanic and many crews with only one or two Hispanics. The 192 operations in the survey that employed Hispanics averaged two per crew.

4.2 Questionnaire

The average and median employment time of Hispanic logging workers was seven and six years, respectively. This would put the average starting employment date for most Hispanics around 1999 or 2000, which is towards the end of the large Hispanic population growth in the South (Kochhar et al. 2005). A possible explanation for not having shorter average employment time is the fact that the H2B visa cap has been reached early in the fiscal year since 2003 (Ferrier 2004, Murphy 2004, Siskind and Ballentine 2003). This would limit the availability of new Hispanics in the logging industry, since the H2B is the only legal visa that a migrant worker can obtain to work on a logging job.

Hands-on training ranked as the most effective method for training Hispanics. This was the only non-resource based training method that was listed. It involved no spoken or written communication, only physical demonstration of a safe operating practice with the Hispanic worker then trying to repeat the practice. The use of a bi-lingual Spanish-speaking workers or attending local safety training programs presented by Spanish-speaking instructors were the next two most effective methods for training Hispanics. This approach is popular in the construction industry where many organizations are creating and using methods such as this to train their Hispanic workers (Brooks 2003, OSHA 2002, Ceniceros 2001). Even though the use of hands-on training is favored by the respondents as the best approach to safety training, it might not be effective without the use of a bilingual employee/translator. This is due to the fact that an employer is required by OSHA to relay safety training to their employees in a method they understand. To find out if a Hispanic understands a safety training method taught through hands-on training, a bilingual employee/translator would be needed to translate any questions or comments.

The three methods for training Hispanics through written or visual communication were rated the least effective. This could be due to the low education levels of foreign-born Latinos; 62% have less than a high school education (Kochhar et al. 2005). Low education levels could relate to low literacy levels which would make written safety training materials and videos with Spanish subtitles difficult to understand. Other studies identify education and literacy levels of

Hispanics as specific issues of concern when conducting safety training (Anonymous 2003, Elkind et al. 2002).

Respondent's opinions of the best way to train Hispanics were similar to the actual methods used by the respondents. The majority of respondents used only hand-on/demonstration type training, while a large percentage also used an employee or hired translator/interpreter to conduct safety training. Interestingly, 29% of respondents used only safety meetings or only talked about safety in a general sense or when needed. These methods use no aides designed for training Hispanics, and therefore, the effectiveness of these methods must be questioned. Another interesting note is that only 12% of the respondents use a combination of any of the previously mentioned training methods. It would be logical to assume that a combination of training methods would be beneficial on crews with more than one Hispanic worker since each one may have a different level of education and English comprehension. A combination of different training methods is the approach that OSHA and the Hispanic Contractors of America Inc. (HCA) used when they formed an alliance to promote safe and healthful working conditions for Hispanic construction workers (OSHA 2002).

5. ACKNOWLEDGEMENTS

Partial funding for this study was provided by the U.S.D.A. Forest Service Forest Operations Research Unit at Auburn, AL. Study cooperators included members of the Forest Resources Association's Southwide Logging Safety Committee, Davis-Garvin Agency, Inc., Amerisafe Corp., Forestry Mutual, Inc., Georgia-Pacific Corp., South Carolina Timber Producers' Association, Manry-Rawls Agency, Inc., and Potlatch Corp.

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Extended Working Shifts: Are They Applicable to the Southeastern United States?*

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Abstract
Logging operations in Scandinavia, Canada and the Lake States of the United States have used non-traditional (extended) working hours to increase their production for many years. However, extended shifts are uncommon in the southeastern United States. A major limitation in implementing extended working hours in the southeastern states is that logging business owners do not have a full understanding of the costs and benefits associated with extending shift number or length. This two-year project will test two questions. The first is whether extended shifts increase production and control unit costs. Safety, night productivity, employee turnover, and tax implications of machine depreciation are just some of the tangible and intangible costs and benefits that will be evaluated. The second question is whether an acceptable number of harvest cuts are suitable for extended work hours. These harvest parcel (tract) variables need to be identified and their impacts quantified. The objectives of this study are to: (1) characterize the extended shift work hour methods used in the Lake States, (2) identify factors for tract selection, (3) identify loss control and safety issues, (4) quantify the differences in machine costs between shingle shift and extended shift, and (5) develop a business decision-making tool to aid logging business owners in quantifying the costs and benefits of extended work shifts. The paper presents some initial findings from interviews with logging contractors who have successfully, and not so successfully, implemented extended working hours.

Keywords: extended working hours, logging methods, work scheduling

1. INTRODUCTION

Logging operations in Canada and the Lake States of the United States have used extended working hours for many years in order to maintain production, often due to ground conditions. Extended shifts are so common in Canada that at forestry training centers in New Brunswick and Quebec, students are required to operate equipment for 24 hours/day, 7 days/week for real life experience (Turtle, 1997). However, extended work schedules are uncommon in the southeastern United States (Alabama, Florida, Georgia, Louisiana, Mississippi, North Carolina, and South Carolina). Logging business owners in the southeastern states are wary of extended working hours because there have been limited incentives and pressures for experimenting. From discussions with loggers and consultants, we find that the most common methods for increasing logging production in the southeastern states is to add processing

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 513-522.*

mechanization, increase machine size, balance the system, or add a second crew with a complete second set of logging equipment.

There isn't a specific definition of extended working hours because there are so many options available. Extended hours can be two overlapping day shifts where overlap hours are used for maintenance; three shifts per day; 12-hour shifts; more days per week; or other options for extending working hours. In addition, some businesses may employ a rotating shift schedule. The production goal set by logging business owners will be a factor in determining the number of extended scheduled working hours needed. This project will explore the logging costs associated with a variety of production levels.

Articles about extended work hours have become frequent in trade magazines within the past few years. While some of these local and regional publications have profiled experiences of logging businesses using extended work hours, none have provided adequate business accounting detail for decision making and analysis of extended work hours in the southeastern states. Many of these articles portray Canadian businesses. It is difficult to compare these businesses to the southeastern states because of the differences in income expectations, labor demand, wood storage and transportation, tax laws, accounting procedures, governmental regulations, and land ownership patterns.

Two questions need to be addressed in order for business owners to make sound decisions. The first is to determine whether logging costs can actually be decreased by extending working hours in the southeastern states. Safety, night productivity, employee turnover, impact of delivery quotas, crew supervision, and tax implications of machine depreciation are just some of the tangible and intangible costs that need to be evaluated.

The second question to be analyzed is the selection criteria used to determine tract (parcel of land) suitability for extended working hours. If a tract has sensitive areas, such as streamside protection zones, it may be difficult to avoid them in the dark. In addition, light conditions may change the operator's depth perception in rough terrain and shadows may make rocks or gullies more difficult to see. Equipment noise, log truck traffic, and other logging-related variables can become factors in tract selection when working near the wildland urban interface.

The objectives for this study are to:

1. Characterize the extended work shift methods used in the Lake States,
2. Identify factors to consider for extended work shift tract selection,
3. Identify safety issues related to extended work shifts,
4. Quantify the differences in machine costs between traditional and extended work hours, and
5. Develop a business decision-making tool to aid logging business owners in determining whether or not to attempt implementing extended work shifts.

The goals of this research are to provide the logging community a thorough analysis on the benefits and costs of extended work hours and to develop a decision-making tool to aid in the determination of implementing extended shifts.

2. RATIONALE AND JUSTIFICATION

2.1 Can extended working hours actually decrease per unit logging costs?

According to a recent report (Stuart et al, 2005), logging costs have increased 35% from 1995 to 2004. Prices paid for logging services have decreased by 10%. Logging businesses are looking for ways to reduce their costs or increase the value of their services or products to stay in business. Working extended hours is an opportunity that loggers may use in an attempt to reduce unit logging costs and make a firm a more valuable producer to a procurement organization.

The major cost components for a logging business are: administrative overhead, contract services, insurance and taxes, labor, consumables (including fuel), and equipment. On average, equipment may account for just 15% of these costs (Stuart et al, 2005), but it is one of the few categories that can be controlled through business decisions. The current trend is that small and mid-size firms are extending equipment life to minimize risk from debt service. One way to increase debt retirement may be to work one set of logging equipment for extended hours.

Machine Costs

New logging equipment is an expensive capital investment. The manufacturers suggested retail price of a new 215 hp, rubber-tired grapple skidder ranges from $185,000 to over $200,000 (USD) depending on the options included. Most logging businesses include several additional pieces of expensive heavy equipment, such as feller-bunchers and loaders.

Because of the high level of capital investments required, businesses need to keep these machines productive. The number of scheduled machine hours (SMH) for a typical logging operation with one feller-buncher, two skidders and one loader is about 2000 hours per year. This generic number allows for fifty, 40-hour work weeks and two weeks for vacations, holidays, or other non-productive periods. It is expected that extended work schedules would increase machine hours which is one of the basic variables used in calculating machine rates. It is expected that increased scheduled machine hours will increase the total production for a set of equipment over a weekly or yearly basis, while reducing the period of debt repayment and finance costs for a given level of capital.

A machine rate method is typically used to determine the cost of producing a unit of wood (Brinker et al, 1989). This method provides an average yearly cost over the life of the machine and only accounts for straight line depreciation. Table 1 displays a machine rate analysis that offers a simple comparison of a variety of extended work hours. The basis for the production and cost comparison is a 215 hp rubber-tired grapple skidder. This is just one piece of equipment that may be found on a logging operation. To perform a full cost analysis, all pieces of equipment would need to be included. But, since different logging operations use different mixes of equipment, a single skidder is used to display some of the cost differences that can be expected from different schedules.

For an arbitrarily chosen production rate of 26.4 green tons/SMH, the traditional schedule (2000 SMH/year) costs $2.65/ton of wood produced. In the first alternative (Alt. 1), the annual number of scheduled machine hours is increased from 2,000 to 3,000. It is assumed that the machine will be traded in at the same number of machine hours (10,000), which reduces the machine life to 3.33 years. Alternative 1 reduces the cost of producing a single ton of wood by $0.14. In the second alternative (Alt. 2), the scheduled machine hours increase to 4,000 hours/year, and the life of the machine is reduced to 2.5 years. This alternative results in a $0.21/ton cost reduction as compared with the traditional schedule. Alternative 3 is displayed to show the estimated machine rate impacts of adding a second set of equipment and crew. As expected, the cost of producing a ton of wood under this alternative is the same as that calculated for the traditional schedule ($2.65/ton).

Table 1. Machine Cost Comparisons

Skidder	**Traditional Schedule**	**Alternative 1 3000 SMH/Yr**	**Alternative 2 4000 SMH/Yr**	**Alternative 3 Traditional Schedule with Two Machines**
Purchase Price ($)	207400	207400	207400	Values are twice the traditional schedule
Life (yrs)	**5**	**3.33**	**2.5**	
Horsepower	215	215	215	
Salvage ($)	41480	41480	41480	
Depreciation ($/yr)	31664	47544	63328	
Interest ($/yr)	14103	14935	15762	
Insurance ($/yr)	10370	10370	10370	
Fuel & Lube ($/PMH)	15.46	15.46	15.46	
Repair & Maintenance ($/PMH)	23.75	23.75	23.75	
Tires ($/PMH)	0.76	0.76	0.76	
Labor & Benefits ($/SMH)	18.00	18.00	18.00	
Utilization Rate (%)	60	60	60	
SMH/Year/Machine	**2000**	**3000**	**4000**	
Production Rate (tons/PMH[a])	44.0	44.0	44.0	
Production Rate (tons/SMH)	26.4	26.4	26.4	
Number of machines	1	1	1	2
Fixed Costs ($/SMH)	28.07	24.28	22.37	56.14
Operating Costs ($/SMH)	41.98	41.99	41.98	83.96
Total Costs ($/SMH)	70.05	66.28	64.34	140.10
Cost per ton ($/ton)	**2.65**	**2.51**	**2.44**	**2.65**

[a] PMH is the portion of the scheduled machine hours that the machine actually works. PMH equals SMH reduced by the utilization rate.

The potential costs and benefits need to be explored to determine the differences that may be expected under extended work hours. Although the machine rate calculations provide a quick method of comparing costs, they do not reflect real life business accounting methodology. Some of the questions to be explored are:

1. Are machines and workers as productive in the extended hours as compared to the traditional work hours? Does the utilization rate change?

2. Which method of calculating depreciation is most advantageous to use when working extended hours?

3. Are machines replaced at the same number of total machine hours as under the traditional work schedules?

4. Are repair and maintenance costs the same with extended work hours as compared to traditional work schedules?

Many of the normal machine costing procedures may be appropriate to apply to the machines used on the extended work schedule. The regular scheduled maintenance that is normally performed after a certain number of machine hours will not change, but those maintenance costs will be borne in a shorter time frame under the extended work hours approach. For example, the oil change schedule for Alternative 2, double the scheduled machine hours as compared to the traditional working schedule, would require oil changes be performed twice as frequently as those for the machine used in the traditional working schedule.

Some of the common assumptions used when determining machine costs will not apply to machines that have been operated for extended hours. While maintenance costs will be incurred in a condensed time frame, the repair rates may change. If a machine is working after dark under poor lighting conditions, will operators drive over terrain that they would have avoided during the day? Will the additional bumps and scrapes due to poor lighting increase the repair costs?

On the other hand, because the machines are newer and replaced on an accelerated timeframe, will the repair and maintenance costs decrease? Some contractors working on a traditional work schedule may delay scheduled maintenance until the crew moves to another tract, the weekend, or a rainy day. Maintenance delays of this type could add to the wear and tear on the equipment. When two crews rely on the equipment, the maintenance schedule may be adhered to more strictly. Will two or more operators provide better daily maintenance than the traditional one person per machine per day? These questions need to be addressed to provide an adequate comparison of the costs associated with the alternatives.

Other Costs

Inventory

A larger inventory of common repair parts (hoses, oil and filters) may be needed because supply vendors will probably not be open during the extended work hours. When machines are used for extended hours, repairs will need to be performed quickly because the down time could potentially affect more than one crew. In some areas, vendors have been very helpful by opening day or night for emergencies. One crew that was interviewed was found to have a supply trailer filled with spare parts supplied by the vendor. The vendor inventories the trailer contents and invoices the logging business for products removed. This is advantageous in reducing equipment downtime, but many companies may not be able to have this in-woods inventory. It is unknown whether there is a price premium paid to have the supply trailer on site.

Employee Turnover

We suspect that employee turnover may be greater when employees are required to work extended shifts. If the operation requires employees to change shifts, work longer hours, or work a permanent evening or night shift, we expect that employee turnover may be higher than on crews working traditional logging work schedules. Many people do not want to work evening or night hours. Social affairs and other domestic activities are often oriented to a traditional work schedule. One logging company that worked extended hours for over a year reported that they had trouble getting people to work on Friday nights because of high school football. On the other hand, another crew that has operated under an extended working hour schedule for two years said that they have only lost one person due to the work hours. In fact, the flexibility to switch between shifts has proven to be advantageous to two separate logging operations.

Many forest workers do not receive any formal training for their responsibilities on a logging crew. On-the-job training is commonly provided by the employer or crew boss. It can be difficult to assign a cost for this training. If extended work hours increase the rate of employee turnover, additional costs for training will be incurred. Our current sampling of contractors is too small to make a determination on the impact of work shifts on the costs for employee training.

Wood Quotas

Mills often use delivery quotas to control their inventories. Are the extended shift operations impacted more than those using traditional work hours? Are extended shift operations issued quotas that are in line with their normal weekly deliveries? If not, what are the crew owners doing in response? Moving to tracts containing products that are not on quota is typically the first response to quotas, but not all tracts are suitable for extended work hours. Alternatively, do crew owners lessen the impact of quotas by laying off employees or alternating work schedules?

Lighting

There will be some initial costs to starting extended work hours if they involve working at night. Task lighting, such as additional lights mounted on equipment, pole lights in areas of concentrated activity, and flashing log load lights are just a few of the costs that may be incurred. Lighting requirements for highway work zones have been documented by the National Institute for Occupational Safety and Health (NIOSH) for road work zones (Pratt et al., 2001), but none are available for forest operations in the United States.

System Optimization

In addition to actual work schedule changes, businesses also differ on how work is implemented during extended work hours. A typical clearcut harvest operation may include one feller-buncher, two skidders, and one loader. Some operations could run this same set of equipment for additional hours each week to increase production and reduce overall costs (Alternatives 1 or 2). Another option is to add a second cutter to the daytime operations and concentrate on skidding (dragging cut wood to a centralized location), merchandizing (cutting the wood to mill specifications), sorting (separating different products into piles), and loading trailers during the night operations (Mims, 2005). This option helps to avoid problems associated with tree selection in thinnings after sunset. Another crew only processes wood at roadside and loads it onto trailers at night. Using a processing head allows the operator to safely buck the logs at night while obtaining the greatest value for each log. Most businesses that use non-mechanized operations, such as chainsaw felling, usually limit these activities to daylight hours due to worker safety concerns.

Some businesses work a smaller crew after dark because of equipment limitations. Cable skidder operations do not operate after dark, since the operator has to get out of the cab to hook up logs. These night crews may focus on merchandizing, sorting, loading and hauling at night. Some cable skidder operations have added a grapple skidder to their logging equipment fleet for shifts after sunset. With a grapple skidder, operators do not have to exit the safety of the machine's cab to obtain a load of wood to drag (skid) to the landing.

Crew Organization

A business may need additional crew supervisors for the extended hours of work. Finding someone who can use good judgment to make decisions without having to call and wake the owner can be a difficult task. Since many logging businesses are small, owners may be reluctant to have the level of open communication needed to empower their crew leaders.

Logging contractors can run a variety of shift and work hours to increase production. Extended hours could be anything from working longer hours each week day with weekends off, to a 24 hours/day and 7 days/week schedule. One Canadian operation tried a variety of shifts, but finally settled on one where they work four nights and five days with the night crew ending on Thursday night with a long break before starting the day shift on Monday mornings (Fullerton, 2003). Another Canadian operation works four 10-hour days Monday through Thursday, 8 hours on Sunday evening, and 8 hours Friday morning. The crew goes home on Friday afternoon and returns to the logging camp on Sunday (Lammers, 2003). In Mississippi, a clear-cut logging operation has two shifts, a day and an evening shift. The evening shift starts at 3:30 p.m. and ends at 11 p.m. (Rottgering, 2004). It may take time and patience for a business to find the right work schedule to be successful at increasing their production.

2.2 What are the safety issues related to extended working hours?

It is expected that workers would be more susceptible to twisted ankles and related safety problems when working in uneven terrain and downed timber after dark, even with additional lighting. For this reason, many operations choose to use only mechanized equipment after dusk. Workers can operate most mechanized equipment from the safety of the machine's cab, which reduces the risk of slips, trips and falls. It is unknown if working extended shifts will change workman's compensation rates. Insurance rates can be increased for logging companies while they are working in timber salvage operations, which have an increased worker safety risk, but many insurance companies assume that salvage logging includes chainsaw work. It is unknown if the insurance rates in the southeast will change with extended work hours.

Initial contacts with insurance companies indicate that workman's compensation insurance rates are not affected by working after dark. Insurance retailers don't have any guidance regarding rate modifications due to extended work hours. Differences will only be expressed as loss history accumulates. Two companies that were contacted are not aware if any of their customers are operating after dark. One company reported only allowing skidding and loading after dusk, with no rate modification.

One company reported that they do not write workman's compensation insurance policies for hauling after dusk. Their records indicate that many accidents involving log trucks occur at dawn and dusk. Most of these accidents are side impacts with the log trailer because of poor lighting on the trailer, even when the trailers meet state regulations. Reflective tape down the trailer's sides, rear lights, and strobe lights on the trailing logs are not enough to prevent these side impact crashes. For these reasons, they do not write workman's compensation policies for hauling logs in the dark.

This same company does not provide workman's compensation for felling after dark because they think it is inherently dangerous. Even though the company could not cite specific data regarding increased felling accident rates after dusk, they felt that it was an unacceptable risk for the company's shareholders.

Lights on hard hats, reflective vests, and additional lights on equipment are some typical safety features added for employee safety when working in the dark. Additional lighting on log landings may also be needed because of the large amount of interaction that occurs in that area. Typically, skidder operators are busy pulling logs onto the landing, the loader operator is selecting wood to move into separate piles or loading wood onto a truck, and other trucks are backing in to be loaded. Landings are a dangerous working area during the day and the hazards are compounded after the sun goes down. If operations are not adjusted to reduce the activity on the landing after sunset, additional safety precautions on the landing are a necessity, not a luxury.

2.3 What are the variables that impact tract selection for extended hour operations?

Noise

The ownership pattern of timberlands plays a large part in the decision to select a tract for extended work hours. In Canada, large parcels of timberland are owned by the government. Logging equipment noise from working extended hours will not usually impact adjacent landowners. In the southeastern states, the timberlands are often near the wildland urban interface or near rural homes. Equipment noise is a concern in these areas during extended working hours.

Harvest Type

The type of harvest cut plays a major role in determining tract suitability for night logging. In a typical southeastern thinning operation, trees to be removed are selected by the equipment operator. Felling machine operators select forked and diseased trees for removal. In the dark, tree characteristics and basal area may be difficult to discern, and may result in quality control issues. In other thinning operations, trees to be removed may be marked with a slash mark of paint across one side of the tree bole. Again, these paint markings could be difficult to find in the dark. Thinning (marked and unmarked) operations could limit the felling portion of the operation to daylight hours to ensure quality tree selection and spacing. In clearcut operations, this is not as much of an issue.

Road Infrastructure

The road infrastructure also plays a role in working extended hours. In Canada, roads within large timberland parcels are owned by the government, so many of the haul miles are on roads with limited access. In the southeastern states, loaded log trucks haul a large percentage of their loads over county roads. Safety issues surrounding log transport at night become even more important when there are mixed types of traffic on a road. Many states have laws regulating the amount of overhang that is allowed from the rear of the trailer after dark. Others require a strobe light to be mounted on the longest log. If hauling after dark becomes more common, states may further restrict their transportation regulations.

Terrain

Not all sites are applicable to logging in the dark. When working in steep terrain, equipment operators may need to pick the safest travel route between trees, and this may be more difficult in the dark. Uneven terrain or small ravines may not be as visible in the shadows of the night work lights. This provides additional incentives for some operations to limit felling to daylight hours.

Sensitive Areas

Extra precautions are often needed when working near sensitive areas, such as streams. Cutting timber in these areas usually requires directional felling. In the dark, the sensitive area may be beyond the lit working area, but within the tree's length, increasing the chance of having a tree top land in a protected area. The logging crew must take special protective measures to either log adjacent areas during the daylight hours, or adequately mark the sensitive areas for avoidance after sunset.

3. SUMMARY

Within the next two years, we hope to address the concerns outlined in this paper. Interviews with loggers will identify the variety of methods that they have used to extend working hours, what changes they have made to their operation to make the work schedule successful, and whether they plan to continue the extended work hours. In addition, loggers will be questioned about accident rates, crew productivity, tract selection and availability, and the impacts of delivery quotas. These interviews will be held in both the Lake States and in Southeastern States.

Financial aspects of an extended work hour operation may be different than those incurred under a traditional work schedule. Interviews will be held with tax attorneys and tax accountants to identify the tax advantages and disadvantages of working extended hours. The data collected from these interviews and those with the loggers will be compiled and a business decision-making tool will be developed.

Logging companies need to find ways to reduce their costs, while maintaining a desired standard of living. If loggers have to work more hours than they're currently working, many would rather find another business. But, when armed with more business cost information and adequate planning, business owners may be able to provide more reliable work schedules for employees, lower the cost to product a unit of wood, and raise profits.

4. ACKNOWLEDGEMENTS

Funding for this project was provided by the USDA Forest Service Southern Research Station, Auburn University School of Forestry and Wildlife Sciences, and the Wood Supply Research Institute.

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2006 Council on Forest Engineering (COFE) Conference Proceedings: "Working Globally – Sharing Forest Engineering Challenges and Technologies Around the World" Coeur d'Alene, July 22-Aug 2, 2006

Rethinking Educational Models for Natural Resource Students*

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Abstract
In recent years there has been concern expressed over declining enrollment in forest engineering and operations graduate programs. Additionally, there has been increasing debate about the nature and organization of future natural resource education in general. Central questions include: How do we balance breadth versus depth of knowledge in our students? Are the knowledge and skills sets necessary for professional success in management versus research disparate and divergent, or congruent and complementary? Should separate educational tracks be developed for students interested in these different career paths? If differentiation should occur, should it begin at the undergraduate or graduate level? How do we achieve integration across disciplines in addressing management and research problems? Should we promote interdisciplinary students, interdisciplinary research teams, or continue to focus on disciplinary training and specialization? How do we facilitate integration of our students into the broader society they serve? In preparing students for success as researchers, how do we balance the growing social and political emphasis on research directed to problem solving with the institutional trajectory of specialization that traditionally has rewarded contributions to basic science and the scholarly knowledge base rather than contributions to society directly? These questions are not new, but the social and political context in which they occur has changed dramatically in recent decades. Educational institutions must correspondingly evolve and adapt if they are to continue to function successfully in society.

1. INTRODUCTION

The future of forest engineering graduate education has been sporadically discussed over the past decade. McNeel, Stokes, and Brinker (1999) discussed declining graduation rates in forest engineering and forest operations graduate programs across North America. The authors' recommendations for countering this trend include more effective promotion of the profession as a viable career path and increased funding to support graduate education in forest engineering and operations. While these are key issues in the future of graduate forest engineering and operations education, we believe many of the issues facing the discipline are the same as those facing other forest resources graduate programs and include structuring graduate programs to better fit individual students career goals and aspirations, ensuring the relevancy of research questions, and balancing multiciplinary/interdisciplinary breadth with disciplinary depth.

This broader conversation was continued at the January 2006 National Association of University Forest Resources Programs (NAUFRP) summit "Forest Research for the 21st Century: Defining strategic directions and rebuilding capacity" where graduate education and funding models pertaining to all forest resources programs were discussed. Of the three main

* *The 29th Council on Forest Engineering Conference. Coeur d'Alene, Idaho, July 30-August 2, 2006. W. Chung and H.S. Han, editors. pp. 523-525.*

questions asked during this summit, one was "What knowledge, skills, and qualities will the next generation of natural resource professionals need?" The response to this question included the following skills and qualities:

- Depth and technical competency in a discipline
- Understanding of other disciplines
- Holistic view of issues, problems, and solutions
- Quantitative and qualitative analysis skills
- Ability to communicate effectively to non-scientific and scientific audiences
- Cultural sensitivity founded on academic and real-world experiences
- Awareness of the impact of research on society
- Collaborative skills with knowledge of conflict resolution

While all of these skills are important, it is unlikely a single graduate degree/program can satisfy all items listed above.

An additional recent conversation on the substance of forest resources graduate education has been aired in a series of editorials in *The Forestry Chronicle*. Innes (2005) expressed a concern over the current emphasis of depth (disciplinary focus) over breadth and recommended an interdisciplinary/multidisciplinary education model. Anderson (2005) replied with his belief that there exists a distinction between the educations needs of managers and of researchers, stating that "forest managers first communicate the problem to researchers, who then work together to find solutions" (p. 786). Further, Anderson stated his belief that sufficient interdisciplinary training occurs at the undergraduate levels and therefore is not needed at the graduate level. Instead of multidisciplinary training, graduate students as specialists should be able to work in interdisciplinary teams to solve complex problems.

While these discussions are not new, the context within which we operate as educators has changed over time. Across the spectrum of forest resource graduate education, the very nature of graduate students is changing. Increasingly, individuals are finding that management-level positions require at least a master's degree. This has widened the scope of outcomes students are seeking from a graduate education.

As noted by McNeel et al. (1999) targeted government funding for research in forest engineering and operations has declined. Therefore, in order to conduct forest engineering and operations research under government funding programs, our work must often be only a portion of a larger research question, necessitating a multi-/interdisciplinary approach to solving broad research questions. This is coupled with an increasing emphasis on the policy and decision-making relevance and/or technological products produced under government funding programs. The decrease in government funding has meant that the reliance on private sources of funding, which has traditionally put more weight on the relevancy and applicability of results, for forest-related research has increased.

2. PROPOSED MODEL

We propose a flexible model of graduate education that is appropriate for forest engineering and operations graduate programs as well as forest resources programs in general. This flexible model includes disciplinary grounding, an understanding of science at an interdisciplinary level, and an understanding of how science interacts with society.

We believe that moving entirely to a multidisciplinary model for graduate education as proposed by Innes would be counterproductive. The grounding of a student in a specific discipline is an inescapable reality, is useful to the student, and is a productive component of a graduate education. This grounding can be achieved in a number of different ways, from undergraduate education, work experience, or coursework and will be different for each student.

Second, we believe an understanding of science at an interdisciplinary level is important for all graduate students. Traditionally this has been a component of doctoral programs, but not necessarily master's-level education. If graduates of our master's programs are the individuals who will likely be deciding on the relevancy of research proposals and results, we will serve both the student and the profession well by instilling an understanding of what science is early and at a broad level.

Third, students should develop an understanding of how science interacts with society. This is a key skill required in the development of relevant research questions and practical solutions to problems posed by society. This demand of relevancy is increasingly required by most funding programs.

This proposed model needs to be flexible enough to accommodate specialists as well as generalists, managers as well as academics (contrary to the thoughts of Anderson). There are numerous paths individual students can take to gain the three broad skills listed here. Therefore, the implementation of such a model requires great trust between faculty members within a program.

3. CONCLUSION

We believe this flexible model for graduate education will help to recruit and retain students within forest engineering and operations programs by better integrating forest engineering research into larger issues faced by society and the profession of forest management. This broadening will likely attract a greater variety of students who may not look at a narrowly-focused forest engineering graduate program. Additionally, by allowing flexibility in graduate programs, we will be able to serve the ever-widening scope of educational needs of our students while at the same time increasing the relevancy of the research we conduct.

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