34th Council on Forest Engineering Annual Meeting

Engineering the forest value chain

Quebec City (Quebec) Canada

June 12-15, 2011

COFE 2011 Quebec city

Program

Printable PDF version

SUNDAY June 12

18:00	**Registration** Hôtel Classique, 2815 Boulevard Laurier, Québec

MONDAY June 13

07:00	**Registration** (COFE, COFE + VCO Summer School) Hall - Kruger Building
08:00	**Welcome** - Kruger Building, Room 2330 Dr. Robert Beauregard, *Dean, Faculté de foresterie, de géographie et de géomatique* Dr. Luc Lebel, *Annual meeting Chair*
08:30	**The Extensive and Complex Supply Chain of a Turnkey Logging Contractor of the Boreal Forest** Réjean Paré, *Rémabec inc.*
09:15	**The Challenge of Supplying Timber From Across the USA-Canada Border to Produce Innovative Forest Products** Charles Tardif, *Maibec*
10:00	**Break - Cafeteria Abitibi-Price**
10:30	**The Challenges of Engineering the Forest Value Chain** Jean-François Gingras, *FPInnovations*
11:15	Move for Session 1 or 2

	Session 1 Kruger Building, Room 2330	Session 2 Abitibi-Price Building, Room 1160
11:20	Routing of Self-Loading Logging Trucks in Sweden Dag Fjeld, *Swedish University of Agricultural Sciences*	Forest Biomass for Soil Protection From Machine Off-Road Traffic Dirk Jaeger, *University of New Brunswick*
11:40	Designing Value Chain Improvements for an Eastern Oregon Poplar Plantation Using Terrestrial Laser Scanning Technology Glen Murphy, *Oregon State University*	The Impact of Brush Mats on Forwarder Surface Eric R. Labelle, *University of New Brunswick*

Organizing committee:

Luc Lebel
Université Laval, FORAC

Jeff Benjamin
University of Maine

Daniel Beaudoin
Université Laval, FORAC

Jean-François Gingras
FPInnovations

Sophie D'Amours
Université Laval, FORAC

Denise Dubeau
Ministère des Ressources Naturelles et de la Faune, Québec

Pierre-Serge Tremblay
Université Laval

In collaboration with:

12:00	**Lunch - Cafeteria Abitibi-Price**	
13:20	**FPInnovations Tools to Improve Trucking Management** Dave Lepage, *FPInnovations*	Equipment Mix and Operating Strategies Utilized by Logging Businesses Producing Biomass in the Piedmont of Virginia Scott Barrett, *Virginia Tech*
13:40	Fast Truck: A truck Scheduling System to Improve the Transport Efficiency of In-Field Chipping Operations Mauricio Acuna, *University of Tasmania*	Deep Tillage Can Improve Soil Physical Quality and Forest Productivity David H. McNabb, *ForestSoil Science Ltd.*
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	Air Quality on Biomass Harvesting Operations Dana Mitchell, *USDA Forest Service* **No presentation**	Harvesting Small Trees for Bio-Energy John Klepac, *USDA Forest Service* **No presentation**
17:15	**Business meeting for COFE members** Abitibi-Price Building, Room 1111	

TUESDAY June 14

08:00 17:30	**Field trip** *Following the value chain...from small trees to big profits* Departure and arrival: South entrance of Abitibi-Price Building Coffee offered at the meeting point from 7:45 Spouse Program
19:00	**Social and evening meal (Manoir Montmorency)**

WEDNESDAY June 15

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Value Chain Optimization
Summer School 2011
Challenges in Engineering and Integrating the Forest Value Chain

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Joint program COFE + VCO Summer School

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ROUTING OF SELF-LOADING LOGGING TRUCKS IN SWEDEN

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ABSTRACT

The aim of this study was to map the process which contractors typically use for weekly and daily routing of self-loading logging trucks. 15 hauling contractors from the Södra Skogägarna forest owners association were selected for the mapping. The mapping resulted in a basic process model and 2 main variants. Key performance indicators for both profitability and service were collected for a one-year period. Profitability was measured by net operating margin. Supplier servicer was measured by proportion of transport orders completed within a specified period. The results show that contractor profitability decreased (from 15 % to 1 % net operating margin) with increasing levels of supplier service (from 89.5 to 97 % of orders completed within one month). Within this gradient, those using the complete basic model had an average net operating margin of 4.1 %. Those using a simplified model (with fewer service restrictions) had an average margin of 9.2 %.

Keywords: hauling contractors, truck routing, profitability, service levels

INTRODUCTION

In Sweden, roundwood transport makes up a large proportion of wood supply costs. The high proportion of wood from non-industrial private forest owners and distribution of saw and pulp mills requires the coordination of a number of assortments from scattered harvesting sites to multiple mills. These operations are typically managed by the supply organization (transport service buyer) where central administration contracts transport capacity and then distribute periodic-specific transport goals to regional transport managers and their respective contractors (transport service providers). At the operational level vehicle routing becomes the responsible of the service provider. The supply organization, however normally retains close control over truck transport delivery as a possibility for compensating for disturbances in the other parts of the transport system.

The classic trade-off in the world of logistics is between cost and service. In the forest sector, the most commonly expressed supplier goal is to minimize transport costs for the defined service level. For a contractor the goal it is to maximize profitability within the restrictions of the agreed service level. Much literature is found recommending process improvement both within and between organizations for the purpose of increasing income and reducing costs, however, only a few forest-sector studies are done on this topic. Most earlier studies have been done from supplier, mill and even supply chain perspective, Few, however, have been done from the hauling contractor perspective. Mäkinen (1993, 2001) and Soirinsu and Mäkinen (2009) examine transport contractor profitability purely from a perspective of business strategy and returns to scale. Erlandsson (2008) examines contractor profitability in terms of the task environment which also includes some interfaces with service buyers, but without examining process configuration as an influencing factor.

Aims of this study

The first aim of this study is to map current contractor-level processes for routing of self-loading logging trucks. The second aim is to identify main variants of the process model and see if these differences are linked to contractor service and profitability levels.

METHODS

The study was done in two parts. The first was process mapping and the second was the search for links to service and profitability levels. The process mapping started with personal interviews and the formation of draft processes for individual contractors. When the draft maps for individual contractors were ready the search began for common features linking the different drafts to a general model. Main variants of the general model were then defined and the corresponding service and profitability levels were compared.

Process Mapping

The study was hosted by Södra Skogsägarna, a forest owners association in south Sweden. Multi-truck contractors were randomly selected from each of the organization's 3 regions (East, West, South). The distribution of contractors per region was 6 in the East, 6 in the West and 3 in the South (15 in total). Each of the respondents were contacted first by mail (to explain the aim of the study) and later by telephone (to book time and place for the interview). Participation was agreed to under conditions of anonymity.

The process mapping was based on the methods and nomenclature described by Larsson and Ljungberg (2001) who specify a variant of mapping called design-process where complex structures must be formulated from semantic descriptions in the absence of physically observable activities. Larsson and Ljungberg refer to three levels of detail: process, sub-process and activity. Within this hierarchy any process is assumed to include a number of components including input (which triggers the start of the process/sub-process or activity), activity (which transforms the input), resources (which are needed to do the activity), information (which supports or controls the activity) and output (which is the result of the activity and may be the input for the next activity).

The personal interviews with each contractor also covered a number of themes other than the explicit mapping of the routing process. These included descriptive information on the contractor's enterprise, their cooperation with the service buyer's transport managers and other parameters influencing the contractor's task environment. The interviewer asked direct and simple questions according to a pre-prepared structure allowing the respondent complete freedom to formulate complex answers. The interviewer used a series of empty process diagrams to help formulate the process during the interview. Interviews were recorded on a Dictaphone for future reference. After the completion of the 15 interviews, each contractor's routing activities were defined and named. The draft process maps which were filled in during the interviews were then compared to the recorded protocol and adjusted if required. After this the activities were categorized into sub-processes according to similarities in purpose and level of detail. After this the sub-processes and activities were defined and named.

Service and profitability variables

The chosen service level indicator was the proportion of assigned transport orders completed (all volumes for assortments delivered) within 5 weeks of initiation. This variable is therefore a measure of service offered to suppliers (forest owners with a delivery contract to Södra Skogsägarna). Average values were taken from the service buyers database (based on input from SDC, the central database for Swedish wood transactions). Data was missing for one contractor. The chosen profitability indicator for the contractor was net operating margin defined as the net operating surplus (after financial costs) as a proportion of annual turnover. Net operating margin is a relative term and therefore robust when comparing enterprises of different sizes. Values were available for limited stock companies through the Swedish national database. This data was not available for 4 contractors which had other forms of ownership. The analysis of how enterprise-level service and profitability corresponds with process configuration was done quite simply. Average values of contractor service and profitability are compared between the variants of process configuration. Scatter plots between variables from individual contractors are used to visualize eventual relationships.

RESULTS

The contractors in the study had between 2 and 12 trucks per enterprise and delivered wood to between 5 and 15 mills. Each truck delivered approx 40 000 m3/yr with a typical utilization of 4500 hrs/yr (Tab. 1).

Table 1: Descriptive statistics for the hauling contractors in the study.

	Mean	Median	Max	Min	N
trucks/contractor	4,87	4	12	2	15
mills/contractor	9,4	8,5	15	5	14
m3/yr/truck	47606	39743	100000	32000	14
km/yr/truck	185890	180000	230000	135000	15
delivery distance (km)	80	80	120	50	15
hrs/yr/truck	4525	4500	5405	4000	12

The average annual turnover per contractor in the study was approx. 12 million SEK. The average net operating margin (profit before financial costs as a proportion of annual turnover) was 5 % but varied from -3 % to 15 %. The average service level (% of transport orders completed within 5 weeks) was 93 % but varied from 84 to 97 % (Tab. 2).

Table 2: Service and profitability parameters for the contracting enterprises in the study.

	Mean	Median	Max	Min	N
Net annual turnover (1000 SEK)	12 606	12 873	19434	6309	11
Annual Profit (1000 SEK)	295	206	1123	2	11
Net annual margin (%)	5%	3%	15%	-3%	11
Service level (%)	93,2	94,3	96,9	84,1	14

The typical contractor routing process

After a comparison of all the individual contractor models, a basic model was formed consisting of all the activities which the majority of contractors (8 of 15) used to solve their own routing problems. These activities were aggregated into the 4 sub-processes (Fig. 1). These and their respective activities are described below.

Information gathering (1). This sub-process consists of one activity. Receival of new transport orders (1.1) is a daily activity where the contractor receives new transport orders (delivery responsibility for a specific harvesting site) from the forest owners association. This occurs either through direct contact with the service buyers transport manager or by downloading the new assignments directly from the service buyer's information system. After this sub-process the contractor has a complete list over his transport orders (all harvesting sites where he is responsible).

Preparatory planning (2) consists of 4 activities. This sub-process gives the contractor an overview of the restrictions, priorities and possibilities for vehicle routing. Mill quota follow-up (2.1) is for tracking the contractor's weekly quota for volumes per assortment to de delivered to the respective mills. This activity monitors the volumes delivered so far and how much is left for the days remaining. This activity can also include increases or decreases in the quota if supply or demand conditions require so. Ranking of transport orders (2.2) is when the contractor ranks all the transport orders based on a selection of priority factors. Unless special conditions exists the default priority is based on the data the transport order was assigned (oldest first). Analysis of geographic flow patterns (2.3) is when the contractor examines the patterns of wood flow to see where there exists potential for backhauling. Contact with other contractors (2.4) is for when a suitable wood flow pattern for backhauling exists between contractor transport orders and the contractor makes contact with another contractor to request an exchange of volumes to realize the backhaul. After this sub-process the contractor has a ranked list of transport orders indicating the sequence they should be delivered to meet both supplier and mill service requirements while reducing the proportion of unloaded driving.

Problem solution (3). This sub-process consists of 3 activities. These activities determine how the vehicle routing will be done during the planning period in question. Filtering of infeasible transport orders (3.1) is when the contractor filters out harvesting sites which are temporarily unavailable due to weather conditions or limited opening hours for wood receival at the mill. Clustering of small volumes into whole loads (3.2) is when the contractor locates smaller volumes (of the same mill destination) within acceptable distances to aggregate into whole loads. Search for load sequences (3.2) is when the contractor factors in the working hours of the individual operator and combine loads into sequences that give the operators full shifts that conclude close to their home bases. After this sub-process the contractor has solved the daily routing for his trucks.

Final adjustments (4) – consists of 2 activities. Execution (4.1) is the operators' execution of the individual delivery and detailed planning of the path to each harvesting site for loading. Arranging operator switches (4.2) is when the operators contact each other and agree to an exact meeting place for changing operators between shifts. After this sub-process the contractors routing solution has been executed and operator schedules coordinated in detail.

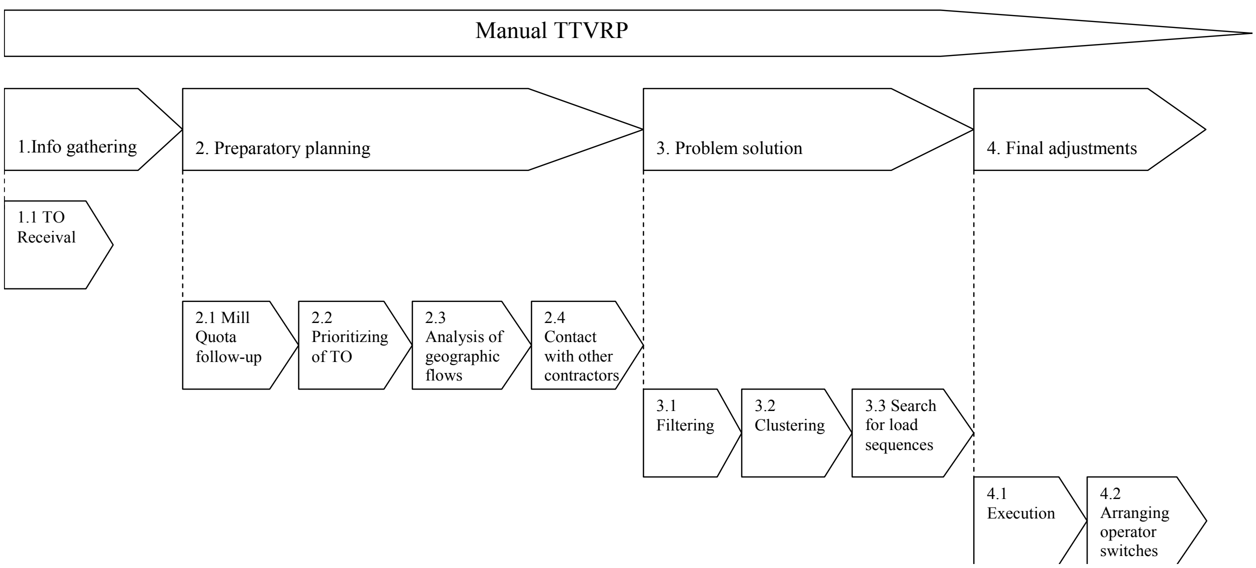

Figure 1: A process model for routing of self-loading logging trucks with 4 sub-processes and 10 activities. The model consists of the activities that the majority of hauling contractors use in their vehicle routing.

Service and profitability for different variants of the routing process

Seven contractors of the 15 studied used another variant of the basic model than described in figure 1. These had a simplified preparatory planning sub-process (2) where follow-up of mill quotas (2.1) was not included in their way of working. Two contractors of the 15 studied used a simplification of the problem solution sub-process (3) where clustering of small volumes (3.2) and the explicit search for optimal load sequences (3.3) was not included in their way of working.

Figure 2 shows that for those contractors working with either the basic model or the variant with simplified preparatory planning (2) profitability decreased (from 15 % to 1 % net operating margin) with increasing levels of supplier service (from 89.5 to 97 % of orders completed within 5 weeks). Within this gradient, those using the complete basic process model had an average net operating margin of 4.1 % while these not limited by quota follow-up (2.1) had an average margin of 9.2 %. Those contractors working with the complete model had higher supplier service levels in all three regions (Fig. 3). Figure 4 shows that profitability decreased with increasing annual operating hours per truck, regardless of which process model the contractor used. However, the contractors with a simplified problem solution sub-process had a higher number of operating hours than other contractors for the same level of profitability.

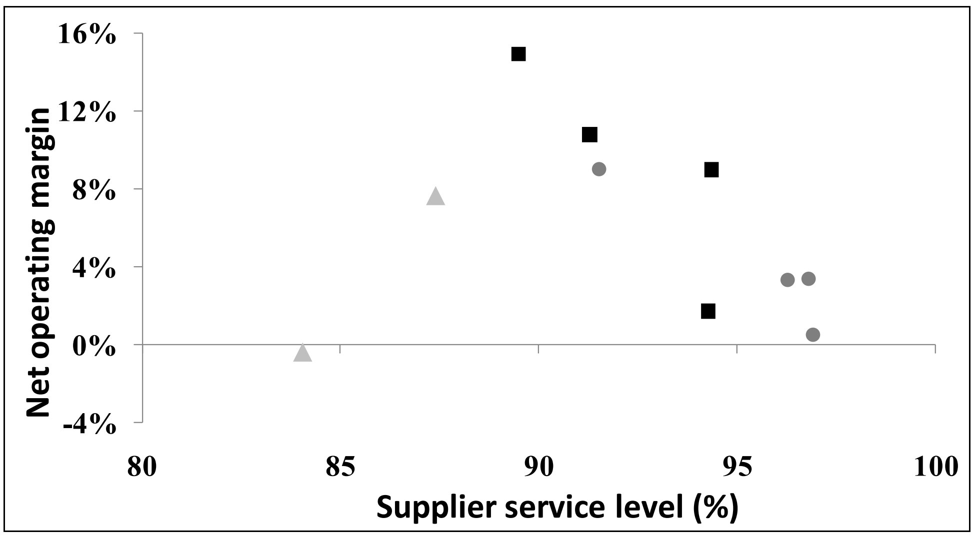

Figure 2: Scatter plot between net operating margin and supplier service levels for 10 trucking companies (circles = hauling contractors with the complete basic process model, squares = hauling contractors with simplified preparatory planning, triangles = hauling contractors that have a simplified solution sub-process.

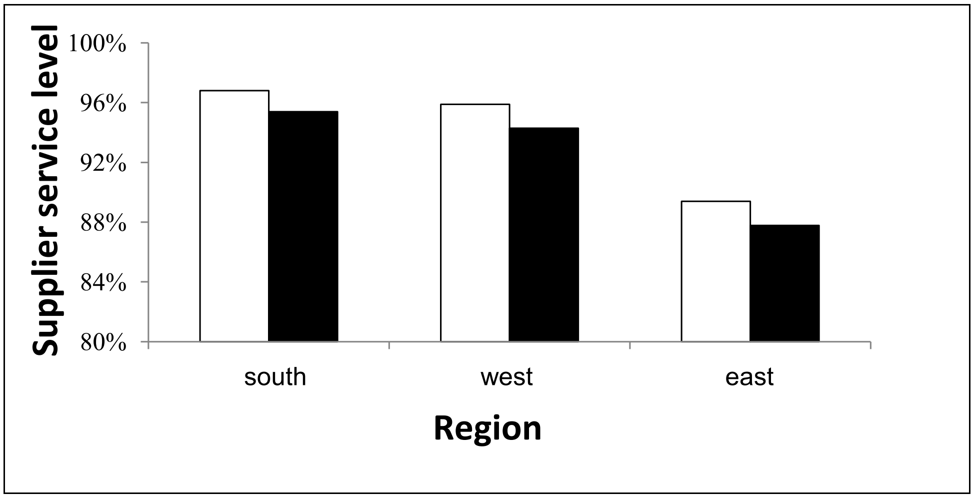

Figure 3: Mean supplier service level for hauling-contractors in each region grouped into whether they had a simplified preparatory planning sub-process or not (black columns = simplified sub-process, white columns = complete sub-process).

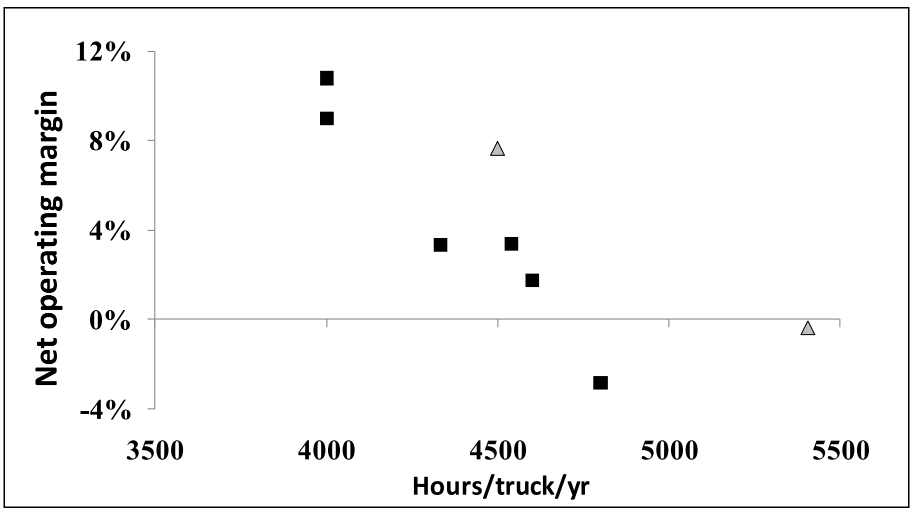

Figure 4: Scatter plot between hauling contractors' net operating margin and the number of annual operating hours per trucks (squares = hauling contractors with a complete solution sub-process, triangles = hauling contractors with a simplified solution sub-process).

DISCUSSION

Karanta et al. (2000) characterizes the logging truck routing problem (otherwise known as the TTVRP) one of the most difficult problems to solve within the world of operations research (OR). Given this, it seems a paradox that roundwood transport works as smoothly as it does. However, the main difference between mathematical OR formulations and practical transport management is the division of potentially large problems into smaller geographic sub-problems. While this poses the risk of geographic sub-optimization, it makes the problems possible to solve manually without advanced decision support systems. Karanta (2000) mentions two particular challenges of solving this problem with traditional OR methods; first, an unusually high number of constraints which must be taken into consideration and second, the difficulty of specifying a general formulation of the goal function. Regarding the first challenge, we can note that the theory of problem solving interprets the preparatory planning sub-process as focusing on the most critical factors of the task environment. In this respect the basic process model presented in figure 1 already at the start of the problem has the opportunity to exclude consideration to certain wood flows and focuses on the most critical constraints.. Regarding the second challenge, a major difficulty in specifying a general goal function is conflicting perspectives between different parts of the system (e.g. supplier vs. contractor. vs. mill). Again, the preparatory planning sub-process of the basic process model captures potentially opposing goals before beginning to address specific sequences or solutions or exclude a high number of potential alternatives (if service priorities can motivate this). Given problems of poor information quality referred to by Ekstrand and Skutin (2004) the solution process used by most contractors also reduces the required flow of supporting info to control constraints and focuses the need for further information gathering on where it supports the most pressing or relevant alternatives.

To summarize, the sequence of activities used by the studied contractors in this study effectively strips down the problem space to its most critical areas. In an extreme case a few priority mills might require immediate deliveries which are only possible to fill from a few priority landings where the critical latest date is near. This limits the number of potential pick-up and delivery points for each truck within the respective contractor's "home territory" to a relatively low number. The contractors can then easily find an acceptable sequence of loads for the day using only knowledge of average trip times. Under these conditions, the possibility for trucks to circulate between the same landing and a few mills can make the routing problem for logging trucks potentially easier to solve than other vehicle routing problems. The consideration of backhaul potentials in logging truck routing, however makes it complex again. Because wood flow patterns for a Nordic hauling contractor are often between competing wood supply organizations the responsibility for exploitation of backhaul potential is normally delegated to the individual contractor who then arranges these in collaboration with other contractors (Audy et al. 2010). Frisk (2002) examined decision support systems for helping to locate potential backhaul flows and Karlsson et al. (2006) mapped the inter-organizational processes for arranging backhauling between contractors. The operational feasibility of realizing these backhaul potentials have been examined in both simulation studies (Fjeld 2004) and empirical studies (Auselius 2009) where the levels of roadside stocks were shown to be one of the most critical aspects for high efficiency. It is in this context when backhauling becomes dependent on a long sequence of deliveries that manual routing begins to resemble an advanced board game.

Effects of the process configuration on contractor profitability

Seen in a theoretical perspective – the typical contractors routing process is about moving through a problem space towards a solution which places the whole system in the goal condition. At each node of the problem space the solver can choose an operator (decision rule) and apply it to get to a new node (state of knowledge) which is hopefully closer to his ultimate goal (in this case, profitability within service restrictions). The series of activities mapped in this study have been interpreted as a process which extracts information about the structure of the task environment and uses this for highly selective heuristic search of the problem space for solutions. The particular advantage of the method is that it makes a potentially complex problem simple. The disadvantage is that it may restrict the problem space too much, thus reducing the degrees of freedom required to find the best sequences of deliveries from a profitability perspective. In this context, both mill quotas and supplier service limits have the same effect – they reduce the number of “legal moves” (degrees of freedom) which can be tested on the way to the next node in the problem space. As a result, the combination of high service demands and a simplified search and solution sub-process clearly reduces the possibility to reach the highest level of utilization and efficiency. In this study the two respondents with the simplified solution sub-process (3.3) worked more hours than the other contractors (with corresponding profitability). These observations are consistent with the logic above. However, there may be a number of explanations for the absence of explicit solution sub-process (3.3) such as a) this decision may be made by others (higher up in the hierarchy) b) there are few degrees of freedom in the task environment or c) the contractor does not have the capacity for further information processing. In general the trend for poorer profitability at high utilization has also been reported by Mäkinen (2001) and has been commonly observed among transport managers. If the above conditions a, b or c are present, increasing transport volumes more cannot compensate for poor planning and may even make the situation worse.

Final comments

This study has used a process-perspective to map the typical contractors methods for logging truck routing in a Nordic context. The process perspective was found to be a suitable for identifying common activities in vehicle routing and illustrating main variants of the process. The sequence of activities, however, varies between contractors and other task environments will result in other models.

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FOREST BIOMASS FOR SOIL PROTECTION FROM MACHINE OFF-ROAD TRAFFIC

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ABSTRACT

Forest industry commonly uses timber harvesting and extraction machinery for safety and economical reasons. Due to its high gross weights, off-road traffic of this machinery has the potential to cause long lasting soil disturbance such as compaction and rutting/displacement. We established three test sites in New Brunswick (Canada) to assess the magnitude and persistence of soil disturbances. To evaluate soil density changes, relative soil bulk densities were derived by relating field soil bulk densities before and after off-road traffic to site specific standard Proctor densities. We also explored the use of forest biomass (residue from timber harvesting such as limbs, branches, foliage and tree tops) as a covering layer (mattress) on machine operating trails to mitigate soil disturbances from machine traffic. Therefore, we applied brush mattresses of varying quantities ranging from 5 to 20 kg softwood brush per square meter and analyzed the soil disturbances resulting from machine traffic on the covered trails. Finally, in a laboratory test we compared the load diverting capabilities of softwood and hardwood brush of varying quantity. The results showed soil bulk density increases in the range of 19 to 46% after single to few passes of loaded forwarders. The brush mattress of 20 kg per square meter showed the highest reduction in soil bulk density increases. Furthermore, when analysing relative bulk density this brush mattress helped to significantly lower the number of trail locations exceeding the 80% standard Proctor density threshold (beyond which plant growth is deemed to be impeded) compared to brush mattresses of less quantity. At two test sites, which were monitored for 5 years to identify potential rehabilitation pattern of soil bulk density with respect to pre-impact values, soil density remained elevated throughout the monitored period. The lab comparison of hardwood and softwood brush indicated a slight advantage of softwood brush for load diversion compared to hardwood brush of same quantity.

Keywords: Brush, forest machinery, relative compaction, soil compaction, soil density

INTRODUCTION

Commercial timber harvesting operations rely on the use of machinery for harvesting and extraction of round timber. While this machinery is mostly used to improve the economics and the occupational health and safety of harvesting operations, its use bears also a high risk of negative impacts such as disturbance of forest soils during machine off-road traffic in forest stands. In Atlantic Canada, the most common harvesting method is Cut-To-Length (CTL) using a machinery system consisting of single-grip harvesters and forwarders (J.-F. Gingras, personal communication, 2008). With increasing payloads (up to 20 metric tons), forwarders exert high loads to the ground, which may result in severe disturbances of forest soils. In our studies, we had the following objectives:

1. assess the magnitude of soil density increases caused by forwarder off-road traffic.
2. analyze effects of brush layers (mattresses) on machine operating trails for mitigating soil density increases.
3. assess the persistence of soil density increases.
4. evaluate load distribution capabilities of softwood and hardwood brush.

METHODS

We established three research sites on forestland in New Brunswick in Atlantic Canada. One site was located at the Canadian Forces Base Gagetown in Southern New Brunswick at 129 m a.s.l. with a 4% terrain slope while the other two sites (Black Brook 1 and 2) were established at the JD Irving Limited industrial freehold forestland district Black Brook in Northern New Brunswick at 250 m and 225 m a.s.l. with terrain slopes of 9 and 3%, respectively. The soil type at the site in Gagetown was classified according to the Unified Soil Classification System as sandy silt and at the two sites in Black Brook as silty sand with gravel and silt loam (Table 1). All soil types showed low plasticity.

Table 1: Soil properties according to the Unified Soil Classification System.

Sites	Particle size distribution (%)				Average organic matter content (%)	Atterberg limits (%)		Classification
	Gravel > 2.0 mm	Sand $0.02 \le x \le 2.0$ mm	Silt $0.002 \le x < 0.02$ mm	Clay < 0.002 mm	Depth (cm) 0-30	Plastic	Liquid	
Gagetown	6.1	43.6	29.4	20.9	5.3§	28.2	28.4	Sandy silt (ML)
Black Brook 1	15.3	42.7	34.3	7.7	5.7	41.6	49.0	Silty sand with gravel (SL)
Black Brook 2	4.5	11.1	58.8	25.6	7.0	40.5	48.0	Silt loam (ML)

§ 0-20 cm

The silvicultural treatments ranged from commercial thinning at Black Brook (site 1) to clear cutting operations on the other two research sites in Gagetown and Black Brook (site 2). At all sites the CTL method was applied. Stand specifics are given in Table 2.

Table 2: Forest stands characteristics.

Sites	Forest cover	Stand age (years)	Silvicultural treatment	Total volume	Volume harvested	% harvested	Average harvested DBH† (cm, on bark)
				$m^3\ ha^{-1}$			
Gagetown	mixed softwood	55	Clear-cut	112	112	100	22
Black Brook 1	white spruce	25	Commercial thinning	142	53	37	11
Black Brook 2	white spruce, balsam fir	89	Clear-cut	160	160	100	24

† diameter at breast height

Trafficking of both harvesting and forwarding machinery was restricted to machine operating trails. The machinery used at all three sites is listed in Table 3 together with their nominal ground pressure as determined by the use of PASCAL ground pressure calculator from FP Innovations. The nominal ground pressure of the harvesting machinery ranged from 41 to 54 kPa whereas the ground pressure of loaded forwarders was significantly higher and ranged from 57 to 91 kPa.

Table 3: Harvesting and extraction machinery with nominal ground pressures.

Sites	Single grip harvester		Forwarder	
	Type	Nominal ground pressure (kPa)	Type	Nominal ground pressure (kPa)
Gagetown	John Deere 120	41	Timberjack 610	57
Black Brook 1	Enviro	50	Rottne Solid F9	73
Black Brook 2	Volvo FBR 2800 C	54	Timberjack 1110	91

To evaluate potential soil disturbance due to off-road traffic of this machinery, we assessed (dry) soil bulk density of machine operating trails before and after timber harvesting and extraction by using a nuclear moisture and density gauge (NMDG, Humboldt 5001 EZ). This device enabled us to do in-place soil density assessments of low disturbance allowing for repetitive measurements at identical locations, e.g., before and after harvesting operations. Soil density at machine operating trails was assessed along transects perpendicular to the trail centrelines. Along each transect density measurement locations were spaced by 0.5 m over the full width of the trails, which were 4.0 m in Gagetown and 3.5 m in Black Brook (at both sites). Two adjacent transects spaced 1.0 m apart comprised a test plot or compartment. Sidewise to the test plots with at least 3.0 m distance from the machine operating trails, control plots with eight or six measurement locations in Gagetown and Black Brook, respectively, were established to monitor soil density at the control areas not impacted by machine off-road traffic.

Figure 1 shows the detailed test layout at the Gagetown research site which was similar to those at the two Black Brook sites. At each measurement location soil density (and soil moisture) were assessed at three depths within the top 20 cm of mineral soil in Gagetown and the top 30 cm in Black Brook. We measured soil densities and soil moisture at the established test plots and control areas pre impact before any machinery entered the sites. After timber harvesting and forwarding was completed we re-measured soil densities and soil moisture at identical locations to identify soil density increase due to machine traffic on operating trails.

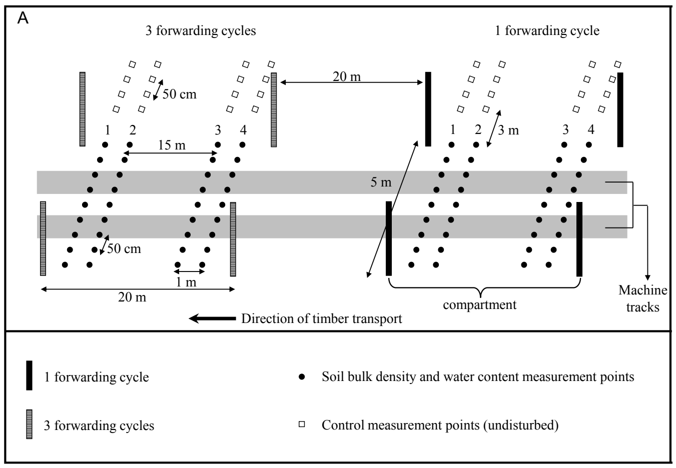

Figure 1: Test layout at the Gagetown research site.

Machine traffic consisted of one or three traffic cycles where a traffic cycle included one inbound and one outbound movement of each machinery (single grip harvester and forwarder) with the forwarder trafficking unloaded into the stand and loaded out. Test plots in Gagetown were exposed to either one or three traffic cycles whereas plots at the Black Brook site 1 were solely exposed to one cycle and at Black Brook 2 to three cycles. Test plots at the Gagetown site and at the Black Brook site 1 remained uncovered from any harvesting debris/brush (branches, foliage, tree tops) during machine trafficking whereas most test plots at the Black Brook 2 research site were covered with softwood brush amounts ranging from 5 to 20 kg per metre squared and had machines trafficking on top of the brush mattresses. The latter was done to investigate any mitigating effects of brush mattresses on soil disturbance and, in particular, on soil density increases due to off-road machine traffic. Once the operation was completed the brush was removed from the test plots and post-impact soil density measurements were performed similar to the procedure at the other two research sites.

To analyze the soil disturbing impact of machine traffic, we calculated the absolute density increases (in g per cm^3) from the differences of soil bulk densities pre and post impact and expressed density increases in percent of the pre-impact densities. To evaluate the severity of soil density increases we then related pre- and post-impact soil densities to site specific reference densities allowing us to determine the relative compaction of forest soils at the test plots. As reference densities, maximum bulk densities (MBD) were determined by standard Proctor tests using soil samples from the research sites. Recent studies in forestry (Zhao 2010) and before in agriculture (Carter 1990) showed significant decreases of plant growth once field soil density is increased to or beyond 80% MBD. At this point most of the macro pores of the soil are lost resulting in reduced gas and water exchange and increased penetration resistance of the soil and, as such, impeded root and plant growth. Figure 2 shows soil bulk densities with related moisture contents as recorded pre and post impact at the Gagetown research site. The inverse parabolas indicate moisture-density relationships as identified by standard Proctor testing to determine maximum bulk density (MBD) and the 80% MBD thresholds (indicated with the dashed horizontal lines).

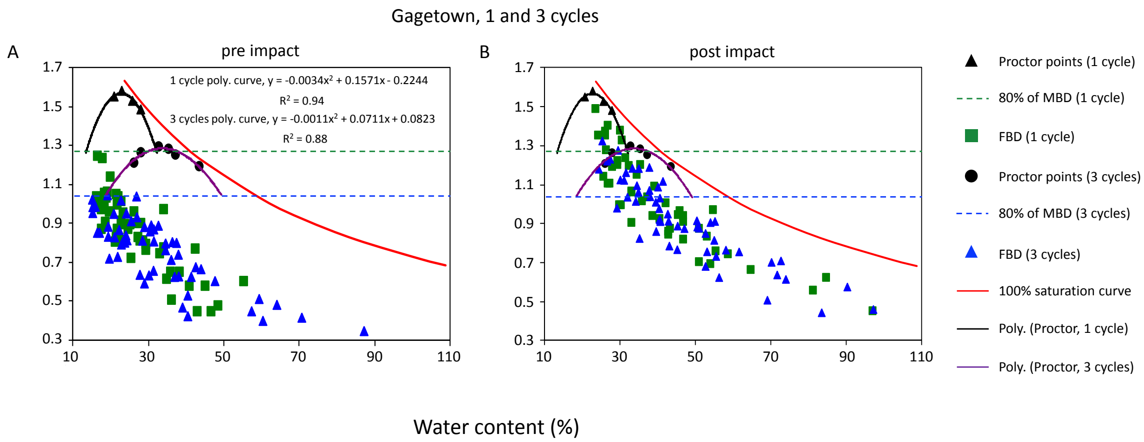

Figure 2: Soil dry bulk densities (g/cm^3) and related soil water contents (%) as determined with the nuclear soil moisture and density gauge at track areas of the Gagetown research site.

The short-term persistence of soil density increases was monitored at two research sites (Gagetown and Black Brook 1) by measuring soil bulk density at all measurement locations every year for five years.

To determine the relative competence of hardwood and softwood brush mattresses in mitigating soil disturbances we performed pilot laboratory testing on load distribution pattern of brush mattresses. By exerting loadings on top of these mattresses and measuring received loadings below the mattresses we wanted to assess the mattresses' competence to reduce peak loadings acting on the soil by transferring loadings into side areas. Using an Instron testing machine, we exerted loads of up to 10 kN on a steel disc of 15.24 cm (6 inch) diameter on top of brush mattresses covering a load box (inside dimensions 37 cm long, 36 cm wide and 19 cm in height) filled with sand (Figure 3A). At the bottom of the box the received loading was measured by three strain gauges mounted to small steel bars of 36 cm length and 2.54 cm width, one of which located in the middle of the box directly below the loaded disc and two strain gauges spaced at 13.7 cm adjacent to each side of the first one (Figure 3B).

We compared the strain gauge responses when loading hardwood and softwood brush mattresses of varying quantity (10, 20, 30 and 40 kg per m^2) to the strain responses we recorded when exerting the loadings to bare sand in the load box (without any brush cover). The tested brush was comprised from green branches from yellow birch (*Betula alleghaniensis* Britton) and balsam fir (*Abies balsamea* (L.) Mill.) with a diameter less than 3 cm since this branch size is most commonly found in brush mattresses of CTL operations in New Brunswick.

A) B) C)

Figure 3: A) Loading piston with disc, B) Three strain gauges at the bottom of the load box, C) Instron testing machine with load box.

RESULTS

Soil bulk density increased at all three research sites due to traffic of forest machinery. Pre-impact soil densities in the range of 0.44 to 1.10 g/cm^3 at all three sites increased due to machine off-road traffic to 0.50 to 1.27 g/cm^3 post impact. At the Gagetown research site and at the Black Brook site 1 mean soil bulk density of the entire trail width increased by 13.2 to 14.0% at test plots exposed to one traffic cycle and by 18.2% on plots exposed to three traffic cycles in Gagetown (Table 4). Despite the brush mattresses covering the operating trail at the Black Brook site 2, we recorded the highest increases of mean soil densities there. Throughout the entire width of the trail, test plots with 20 kg/m^2 brush cover showed the lowest soil bulk density increase of 17.9% while test plots without any brush coverage (0 kg/m^2) showed a mean increase of 33.9%.

Table 4: Mean soil bulk density (ρ_D) increases (in percent of pre-impact density) due to machine traffic for entire trail width and separated in track area and outside track area.

Sites	Traffic frequency (n)	Brush cover (kg/m^2)	Entire trail: n with increased ρ_D (total n)	Entire trail: Mean increase of ρ_D in %	Track areas: n with increased ρ_D (n track)	Track areas: Mean increase of ρ_D in %	Outside-track areas: n with increased ρ_D (n outside track)	Outside-track areas: Mean increase of ρ_D in %
Gagetown	1	0	68 (108)	13.2	41 (51)	19.0	27 (57)	4.4
	3	0	76 (108)	18.2	49 (57)	23.5	27 (51)	8.6
Black Brook 1	1	0	149 (168)	14.0	96 (99)	18.8	53 (69)	5.3
Black Brook 2	3	0	82 (84)	33.9	48 (48)	43.3	34 (36)	22.7
	3	5	80 (84)	29.8	46 (48)	36.8	34 (36)	23.8
	3	10	75 (84)	29.1	46 (48)	45.9	29 (36)	11.4
	3	15	81 (84)	22.1	45 (48)	31.8	36 (36)	11.8
	3	20	77 (84)	17.9	46 (48)	25.5	31 (36)	10.6

Significantly higher increases of soil bulk density were identified when focussing on areas of the operating trail, which were directly impacted by the tracks or tires of the machines (contact area), we named these areas track areas to separate them from the remaining trail area, so called ‘outside-track areas’. In track areas, mean increases of soil bulk density ranged from 0.12 to 0.26 g/cm^3 for all sites. More specifically, we found average increases of soil bulk density of 18.8 to 19.0% after one traffic cycle at the Black Brook 1 site and in Gagetown, respectively, and of 23.5% after three traffic cycles at the Gagetown site. Again, significantly higher increases of soil density were noted when analyzing measurements at track areas at the Black Brook 2 site. Here the mean increases ranged from 25.5% at test plots with 20 kg/m^2 brush cover to 43.3% at uncovered test plots, revealing again the positive impact of brush for mitigating soil density increases induced by machine traffic. Besides the track areas, even the outside-track areas although not directly impacted by the tracks or tires of the machinery, showed an average increase of bulk density of 4.4 to 5.3% after one traffic cycle and of 8.6% after three traffic cycles in Gagetown and up to 23.8% at Black Brook 2. Since the function of the brush mattresses is to divert the loads exerted at the contact area to a wider area (outside the tracks) any brush usage effects higher loadings of the side areas. Soil density increases outside track areas at test plots without brush cover indicated other load transfer mechanisms. Most likely the root network of the forest stand is acting similar to corduroy in transferring received punctual loads to a larger area adjacent to the track area. When analyzing post-impact field bulk densities with respect to site specific 80% MBD thresholds we noticed that some pre-impact measurements were already in excess of this threshold (Table 5). These may be attributed to soil compaction due to machine operations in the past or that our MBDs derived from soil samples in the 0 to 30 cm depth range were too low compared to the relatively high density of naturally developed and settled soils at 30 cm depth where most of the measurements in excess of 80% MBD were taken.

Table 5: Mean soil bulk density measurements exceeding 80% maximum bulk density (MBD) pre impact and post impact due to machine traffic in track areas.

Sites	Traffic frequency (n)	Brush cover (kg/m^2)	Pre impact n >80% MBD (n track)	Post impact n >80% MBD (n track)	Post impact net increase of n >80% MBD (n track)
Gagetown	1	0	0 (51)	8 (51)	8 (51)
	3	0	2 (57)	18 (57)	17 (57)
Black Brook 1	1	0	25 (99)	54 (99)	29 (99)
Black Brook 2	3	0	2 (48)	29 (48)	27 (48)
	3	5	0 (48)	10 (48)	10 (48)
	3	10	0 (48)	10 (48)	10 (48)
	3	15	0 (48)	12 (48)	12 (48)
	3	20	1 (48)	4 (48)	3 (48)

However, after completion of harvesting and extraction using one to three traffic cycles at the Gagetown and Black Brook 1 sites 16 to 30% of all measured soil densities in track areas exceeded the 80% MBD threshold indicating severe compaction and difficult growing conditions for plants and trees because of lost macro pores. At the Black Brook 2 site even 56% (27 out of 48) of all measurements at track areas without brush cover exceeded the 80% MBD threshold. The mitigating impact of brush mattresses becomes very obvious at this site, too, because it reduced the numbers of density measurements exceeding the threshold from 21% (10 out of 48) at test plots with 5 kg/m^2 brush cover down to 6% (3 out of 48) at test plots with 20 kg/m^2 cover. In addition to assessing pre- and post-impact soil densities to evaluate the disturbance caused by off-road machine traffic on operating trails we investigated potential short term rehabilitation pattern of soil density due to frost heave and swelling and shrinking processes. Therefore, we continued to monitor soil density after completion of timber harvesting operations at the Gagetown and Black Brook 1 sites for five years. Figure 4 shows mean soil bulk densities of selected test plots. It is obvious that, so far, soil bulk density remains elevated and in some cases significantly higher compared to pre-impact densities.

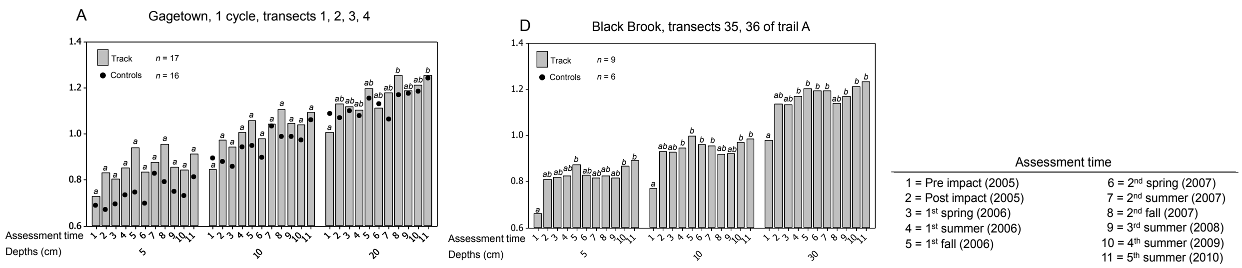

Figure 4: Mean soil bulk densities of test plots in Gagetown and Black Brook 1 indicating pre- and post-impact soil densities at three depths of track areas during the five year monitoring period.

In order to compare the relative competence of softwood and hardwood brush in transferring received loading to larger areas, thus, diverting high punctual loadings to lower dispersed loadings we performed a laboratory test. The capability of brush to reduce punctual loading by load dispersion was tested by loading brush mattresses and comparing the response of the middle strain gauge (vertically located below the loaded disc) to the response of the strain gauge when the load was exerted directly to the sand filled load box without any brush coverage. Table 6 shows the responses of the middle gauge (in micro strains) during the three loadings after performing a first consolidation loading (10 kN) for all scenarios, for bare sand as well as for four brush quantities.

Table 6: Response of middle strain gauge (in micro strains) to three loads (1, 5, 10 kN) when applying no brush (0 kg/m^2) or four brush quantities (10 to 40 kg/m^2) of softwood (SW) or hardwood (HW) brush after one preliminary 10 kN consolidation loading.

Loading	0 kg/m^2	10 kg/m^2		20 kg/m^2		30 kg/m^2		40 kg/m^2	
		SW	HW	SW	HW	SW	HW	SW	HW
1 kN	376	130	159	114	125	76	81	61	64
5 kN	886	298	390	263	301	216	227	188	178
10 kN	1310	370	466	321	362	266	276	233	222

It becomes obvious that all tested brush mattresses contributed to a significant reduction of the received loadings by 65 to 84 % (softwood) or 56 to 83% (hardwood) when compared to the received loading at the 0 kg/m^2 brush scenario. At same brush amounts and loadings, softwood showed a slightly better capacity to disperse exerted loads than hardwood especially at brush amounts of 10 to 20 kg/m^2. At higher brush amounts the differences between the tested fir and birch brush diminished and at 40 kg/m^2 hardwood brush contributed to a lower response of the middle gauge at 5 and 10 kN loading than softwood. A second analysis compared the responses of the side gauges to the middle gauge response to give additional evidence of the ability of the brush mattresses to transfer the exerted loading to side areas. Lateral load transfer would be indicated by relatively high responses of the side gauges. Table 7 shows the average response of the two side gauges in percent of the related middle gauge response.

Table 7: Mean response of two side gauges to received loadings in percent of the loading received by the related middle strain gauge.

Loading	0 kg/m^2	10 kg/m^2		20 kg/m^2		30 kg/m^2		40 kg/m^2	
		SW	HW	SW	HW	SW	HW	SW	HW
1 kN	5.4	31.2	18.2	30.6	20.8	32.2	24.7	28.3	22.4
5 kN	6.1	37.8	21.7	38.3	27.0	39.9	31.2	40.5	33.7
10 kN	4.0	39.8	23.5	40.1	28.5	41.2	31.7	43.1	35.2

The side gauges consistently received higher loadings underneath softwood brush mattresses than below hardwood mattresses indicating a higher capability of softwood brush to transfer loads laterally. Finally, we exposed brush mattresses of 20 kg/m^2 to repetitive loading (five loadings) to find out whether this would affect the capability to disperse the loads exerted on top of the mattresses. Table 8 shows the responses of the middle gauge to multiple loadings. The decreasing response values of the gauge (except for hardwood at the fifth loading) indicate improved performance of the mattresses as continued loading densified the mattresses.

Table 8: Response of middle gauge (in micro strains) to repetitive loading (one to five times).

Loading	Softwood					Hardwood				
	1	2	3	4	5	1	2	3	4	5
1 kN	148	124	127	128	127	147	125	125	122	126
5 kN	330	282	282	280	273	330	297	298	295	302
10 kN	392	342	337	332	328	410	363	359	357	352

DISCUSSION

Our analysis of soil bulk density changes due to off-road machine traffic showed increases of soil density at all three research sites. The most severe change was noted at the Black Brook 2 site where the mean increase of bulk density was 0.26 g/cm^3 in track areas and 0.12 g/cm^3 in areas outside the tracks. Test plots without brush cover showed mean density increases of 43% in track areas while the other two research sites showed significantly lower increases ranging from 19 to 24%. This may be due to the relatively high susceptibility of the Black Brook 2 soil to compaction. The soil type at this site was classified as silt loam having a high degree of fine particles (84% of its mass consisting of soil particles smaller than 0.02 mm) while both soils of the other two sites contained more coarse particles. In addition, the forwarder used at the Black Brook 2 site had the highest nominal ground pressure (91 kPa) of all used machinery at the three sites. This resulted in a high loading impact to a soil type which was more susceptible to compaction. Our recorded soil bulk density increases match the range of increases reported from North American long-term soil productivity sites where the compaction range was 1 to 58% (Page-Dumroese et al. 2006) or from CTL harvesting in mountain pine beetle (*Dendroctonus ponderosae* Hopkins) salvage stands in British Columbia where soil bulk density increased by 6-28% (Phillips 2001). We noted mitigation of machine induced soil density increases when using brush mattresses on operating trails. The mean increase of soil bulk density in track areas was reduced from 0.33 g/cm^3 at test plots without brush cover to 0.19 g/cm^3 at test plots with 15 to 20 kg brush per m^2. However, because of a high variation in all soil density increases we could not prove significant differences of density increases between test plots with and without brush cover. Nevertheless, the analysis of relative bulk density showed a clearer picture; when comparing post-impact soil bulk densities to standard Proctor related maximum bulk densities (MBD) test plots without brush application showed 27 measurements exceeding the 80% MBD threshold while test plots with 15 or 20 kg brush cover per m^2 showed 12 or 3 measurements in excess of this threshold, respectively. This indicates that the use of brush significantly reduces the probability of soil compaction with severe impacts on plant growth. We monitored two sites with increased soil densities due to machine off-road traffic for five years after the machine impact. The recorded soil density data does not indicate any decrease of soil density towards pre-impact density levels although the soils were exposed to frost heave and swelling and shrinking processes. The lack of any slight soil rehabilitation five years after the impact suggests that soil density increases are long-lasting. This corresponds to the findings of Rab (2003) and Anderson et al. (1992) who described significant differences in soil densities even 10 and 25 years after machine traffic. Our pilot laboratory testing of load diverting capabilities of brush mattresses revealed a slight advantage of balsam fir brush compared to yellow birch brush when mattresses of same quantity experienced same loading. More research is needed in this respect.

CONCLUSION

Even few off-road traffic cycles of forest machinery on forested sites can cause considerable increases of soil bulk density with potentially long-lasting effects on stand productivity. Brush mattresses on machine operating trails help to reduce machine induced soil density increase. More comprehensive research is needed to explore the benefits of brush application at different soil and stand conditions. This may help to develop needed strategies to avoid soil density increases in order to enhance sustainable management of our forest ecosystems.

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DESIGNING VALUE CHAIN IMPROVEMENTS FOR AN EASTERN OREGON POPLAR PLANTATION USING TERRESTRIAL LASER SCANNING TECHNOLOGY

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ABSTRACT

GreenWood Resources manages 12,000 hectares of short-rotation (~12 years) poplar plantations in eastern Oregon and Washington. Trees are pruned to a height of approximately 7.5 m to produce a knot-free sheath surrounding a knotty core. The current harvesting and transport system utilizes a feller-buncher, tree-length grapple skidder extraction to roadside, a static delimber/slasher (or processor/delimber), and long length (~ 17 m) off-highway trucking to a centrally-located mill yard. The mill, which is owned by GreenWood Resources' North American Tree Farm Fund (GTFF), produces chips from the upper stem segments and predominantly appearance grade lumber and pallet wood from the lower pruned stem segments.

In summer 2010 sixty forest inventory plots in three stands were measured using a terrestrial laser scanning (TLS) system. A subset of inventory plots (4 to 8) from each stand were felled then manually measured before the stems were extracted, bucked, and transported to the mill. The log-length logs were then debarked, scanned and bucked into shorter lengths (2.5 to 3.8 m) before sawing. Bucking was based on the lumber and value that could be extracted from each short log.

- Based on the data that has been gathered and preliminary analyses of three of the sixty plots, we have been able to:
- determine mill-door values for poplar logs of specific lengths, diameters and maximum sweep tolerances
- show that TLS is not as accurate as mill scanning equipment but does show promise as a pre-harvest inventory tool for determining stand value and log product yields
- establish that the time to gather detailed scan data was about half an hour per plot
  demonstrate how TLS data and optimal bucking could be used to quantify value chain improvements such as adding a veneer line to the mill and reconfiguring the mill's infeed scanning system.

Keywords: terrestrial laser scanning, hybrid poplar, optimal bucking, value chain

INTRODUCTION

The main component of GreenWood Resources' North American Tree Farm Fund (GTFF) is the Boardman Tree Farm (BTF), a hybrid poplar tree farm located near Boardman, Oregon just south of the Columbia River in eastern Oregon. In the summer of 2010 a terrestrial laser scanning (TLS) trial was initiated with a number of goals in mind. One of these goals was to determine if TLS technology could be used to help GreenWood Resources identify and design value chain improvements for their operations.

GTFF contains approximately 10 thousand hectares of hybrid poplar trees. Surrounding land is primarily utilized for agricultural purposes. The area is dry and hot during the summer and dry and cold during the winter. The area is also characterized by windy conditions which result in many trees having lean and sinuosity in the direction of the prevailing winds. The two-dimensional shape of the stems in cross section is elliptical as opposed to circular due to wind loading.. BTF is separated into various age classes and stocking densities on rectangular parcels representing individual stands. Each stand, approximately 70 hectares in size, contains hybrid poplar of the same age and at a particular stocking density. GreenWood Resources grows and harvests trees on a 12 year rotation. Between ages 2 to 5 years trees are pruned in several lifts to a height of approximately 7.5 meters to produce a knot free sheath surrounding a knotty core a. At maturity trees are harvested mechanically by a feller buncher. A grapple skidder is then used for tree length extraction to the roadside where trees are bucked to approximately 17 meters and delimbed by a static delimber/slasher (or processor/delimber). The 17 meter logs are then transported to a mill that is centrally located at BTF and processes all harvested raw timber. Each tree usually yields appearance grade lumber and pallet wood from the lower part of the stem, and chips from the upper parts of the stem that are too small to produce lumber.

Good metrics of the quantity, quality and location of timber resources within each stand are essential for ensuring that wastage is minimized, harvest and volume growth increments are balanced, log products are optimally matched to markets, and the value of the forest is maximized at the time of harvest. Forest owners around the world are evaluating new approaches for obtaining these metrics with the goals of increasing their accuracy and reducing their data gathering costs. Emerging technologies include satellite imagery (Tomppo et al. 1999), harvester data collection and data mining (Murphy et al. 2006), airborne laser scanning (Reutebuch et al. 2005), and TLS (Bienert et al. 2007, Keane 2007).

TLS, which allows production of individual 3D stem profiles, is being used operationally in Ireland to assess stand value and estimate log product yields. It has been studied in a number of trials worldwide. In Sitka Spruce in Ireland, in Douglas-fir in Oregon, USA, and in radiata pine in Australia (e.g. Keane 2007, Murphy 2008, Murphy and Acuna 2010, Murphy et al. 2010) timber was measured with TLS, manually, and with a mechanical harvester. The stem diameters, volume and value recovery estimates resulting from each method were compared. These trials highlighted the potential utility of TLS technology and the conditions under which it might work best. Teobaldelli et al. (2008) have used TLS to measure stem diameters at height of 1.37 or breast height (DBH) (sample of 21 trees) and upper stem diameters (sample of 3 trees) in 14-year old intensively managed poplar plantations in Italy. Average TLS diameters were reported to be within one centimeter of manually measured diameters. Antonarakis (2011) compared manual and TLS measured DBH's in complex riparian poplar forests in France and found a mean bias of less than a half a centimeter (~1.5%).

Siefert et al. (2010) have simulated lumber recovery based on TLS scans of pine stems in South Africa. As far as we have been able to determine, the relationships between TLS measurements and actual mill scan measurements, with respect to volume and value recovery estimation, have not been investigated for poplar stands. Nor has the ability of TLS to accurately scale logs based on log sweep been assessed.

Here we describe the methods we used to compare TLS and mill scan measurements. We also present preliminary findings, based on a subset of our measured stands, plots and stems, and show how TLS measurements can be used to identify and design value chain improvements for GreenWood Resources operations. It should be noted that we are at the early stages of our analyses and that our conclusions may change once all stands, plots and stems have been analyzed.

MATERIALS AND METHODS

In the summer of 2010, when the poplars were in full foliage, each of three stands - low, medium and high stocking densities - was sampled systematically with a random starting point for each stand. The low stocked stand contained 360 stems per hectare (spha), the medium stocked stand contained 550 spha and the highly stocked stand contained 725 spha. Twenty equally spaced circular plots each of 10 meter radius - approximately 3% of a hectare - were located in each of the three stands. Each plot center was permanently marked and all trees in each of the sixty plots numbered and measured DBH. Five standing trees per plot were manually measured for height with an Impulse laser rangefinder .

A Trimble FX laser scanner was used to collect standing tree TLS measurements from two locations within each plot if tree(s) within the plot radius were occluded. The primary scan occurred at the center of the plot and the secondary scan approximately five meters from the plot center. Time to set up the scanner and take two scans per plot was usually less than half an hour.

Random subsamples of plots were selected for felling and detailed manual and mill measurements. There were 8, 4 and 6 plots randomly chosen from each of the stands containing 360, 550 and 725 spha, respectively. Each tree in the randomly selected plots was mechanically felled, delimbed and then manually tagged on the butt for identification at the mill. The subsampled plots yielded approximately 70 trees from each of the 360 and 550 spha stocked stands, and 160 from the 725 spha stocked stand, for a total of 300 trees that were transported to the mill.

From the 300 trees to be transported to the mill, fifty trees from each stocking level were manually measured using calipers for diameter over and under bark (bark was removed with a axe) to determine bark thickness at 0 meters, 1.3 meters (DBH), 3 meters, 6 meters, and then at 3 meter intervals up to a 50 mm top. Trees from the sub-sampled plots were then transported to the mill and bucked at about 17 m (the maximum length for the mill's log scanner. The bottom 17 m stem section was scanned using a Nelson Brothers Equipment scanner (NBE) for diameter and sweep with the bark on. The trees were then rescanned after debarking and optimally bucked to sawlog lengths (8 – 12 ft or 2.6 – 3.8 m). The bucked logs were then sawn in the mill and lumber recovery recorded. Lumber recovery and grade data was combined with lumber prices and chip prices and mill operating costs to determine return-to-log mill-door values for logs of different lengths, dimensions and sweep classes.

The Trimble FX scans were processed using software developed by Treemetrics Ltd. (Ireland) to automatically detect tree locations and stem profiles within each plot. TLS can not "see" through stems, branches or leafy vegetation. In the upper portions of the stem, a taper function was used by the Treemetrics software to automatically estimate diameters for stem sections that could not be seen. Based on the detailed TLS stem profiles, each stem was optimally bucked using VALMAX Optimizer simulation software (developed by the first author). The return-to-log prices were used in VALMAX to provide tree and plot estimates of total recoverable volume and log product yields. TLS based tree, value and product yield estimates could then be compared with manual and mill scan measurements.

In the summer of 2011 we will retake TLS and manual measurements on the remaining plots in all three stands. The purpose of rescanning is to compare annual growth predictions based on TLS and manual measurement methods.

PRELIMINARY RESULTS

The following results are based on trees from three of the 20 plots within one of the three stands; the high stocked stand. The results should be considered as preliminary.

Accuracy of TLS as a pre-harvest inventory tool

We compared underbark diameter measurements at various heights (butt, breast height, 6 m, 9 m, 15 m and 24 m) on the tree for Plots 2, 3 and 6 combined. Overbark TLS measurements were converted to underbark measurements through use of a bark thickness equation. Figure 1 shows the average diameter differences for the TLS, NBE and manual measurement methods. A positive difference means that the average diameter for the first method was greater than for the second method; e.g. the average butt diameter measured by TLS was greater than the average butt diameter measured by the NBE scanner in the mill. There were no NBE data at the 24 meter height because the maximum length of stem that could be scanned by the NBE scanner was about 17 m.

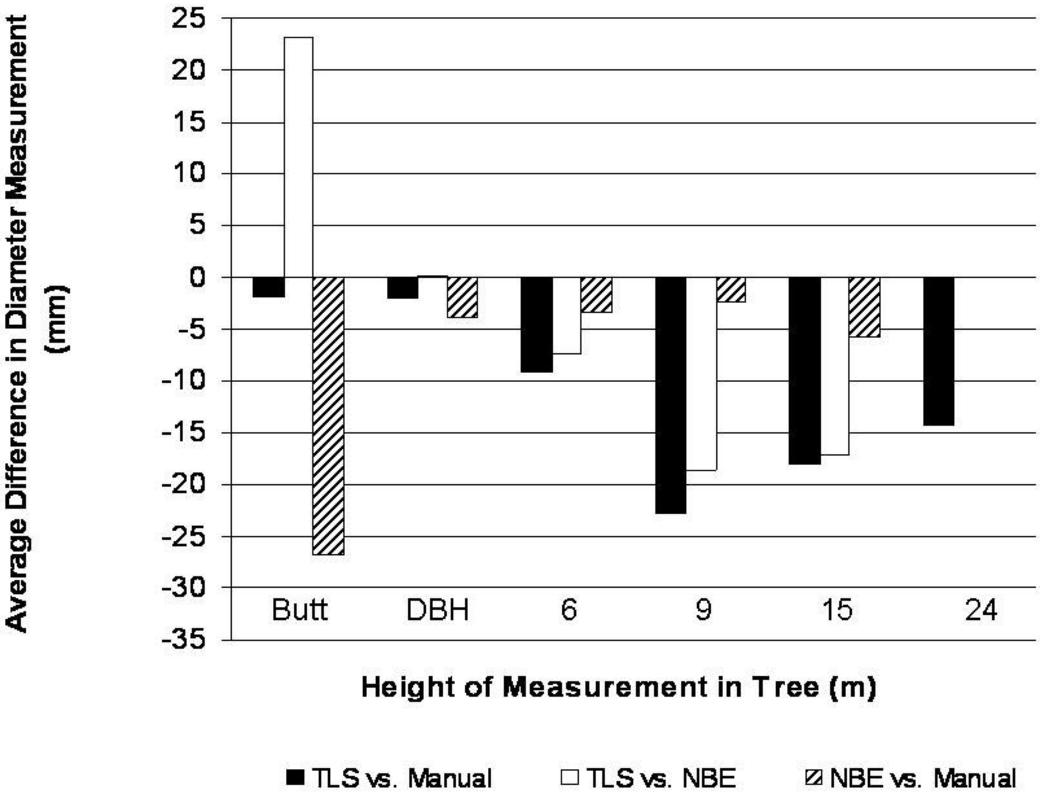

Figure 1: Comparison of average difference in diameter measurement between TLS, NBE and manual methods. A positive difference means that the average diameter for the first method was greater than for the second method; e.g. the average butt diameter measured by TLS was greater than the average butt diameter measured by the NBE scanner in the mill.

At the butt, both TLS and NBE measurement methods underestimated the manual measurements; the underestimate being slightly larger for the NBE method. Accurately measuring diameter at the butt for stems with elliptical, rather than circular, trunks was problematical for the TLS method. The Treemetrics software that is integral to the TLS method we tested assumes that tree cross sections are circular. This is not a good assumption for the wind-influenced poplar stands we were working in. For example, one of the stems had a 40 mm difference in diameter at the butt when scanned from two different directions. We note that the same tree had a 40 mm difference in DBH when scanned from two directions as well.

At breast height the average difference between TLS diameter measurements and diameter measurements taken by the other two methods was lower than those taken at any other height position on the stem. This indicates that TLS measurement is fairly accurate at breast height when compared to the NBE and manual methods; average differences being 0 and -2 mm respectively (0 and 0.8%).

At heights above breast height the accuracy of diameter measurements taken by TLS tends to decrease. At the 6 meter height the average difference in diameter measurement was less than 10 mm between TLS and the NBE and manual methods. The largest average difference in diameter measurement between TLS and the other two measurement methods was at the 9 meter height; an average underestimate of about -20 mm. As noted above the poplar stand had been pruned to about 7.5 m. A heavy whorl of limbs, with some nodal swelling, tended to form above the top of the pruned zone. The Treemetrics software used with the TLS system follows a similar convention to that used on mechanized tree harvesters; namely, diameters further up the stem from a given measurement point can either remain constant or decrease, they can not increase. This convention may have been the reason for the larger difference (underestimate) between TLS measurements and the manual and NBE measurements at the 9 m height.

The average difference in diameter measurement was also large at the 15 meter height, although not as large as at the 9 meter height (an average underestimate of about -17 mm).

There was no NBE data at the 24 meter height; however, the average difference in diameter measurement between TLS and manual methods was assessed; the difference being less than -15 mm at this height. It is unlikely that the scanner was providing actual measurements of the stem at this height in the foliated condition for the hybrid poplar. It is likely that the taper function automatically provided this information; hence the improvement in measurement accuracy.

From breast height to the 24 meter stem height the average TLS diameter measurement was lower than the average NBE and manual diameter measurements. The NBE measurement closely followed the manual measurement at all points measured on the stem. The overall trend indicates that TLS may underestimate poplar stand volume that could be delivered to the mill. Murphy and Acuna (2010) also noted this trend in Sitka spruce, Douglas-fir and radiata pine stands.

Mill door values based on maximum sweep class

The trend in mill-door values was determined by examining the relationship between log value ($ per m^3), log dimensions (length and diameter) and sweep ratio (Figure 2). Small end diameter (SED) and sweep were found to be the key variables affecting value on a per cubic meter basis. Sweep can be defined as the ratio of SED over the center-line displacement, so when the sweep ratio is low for a particular log it means that the maximum center-line displacement is large relative to the SED of that log. Simply put, the lower the sweep ratio the more sweep can be found in that particular log. As expected, the relationship between mill value and SED was positive (bigger logs have higher value per m^3) and between mill value and sweep was negative (the greater the curvature of the log, the less value was extracted from it) no matter what the SED class. The range of values for each SED class was between \$7 per m^3 and \$8 per m^3, indicating that the trend for sweep was similar for each SED class.

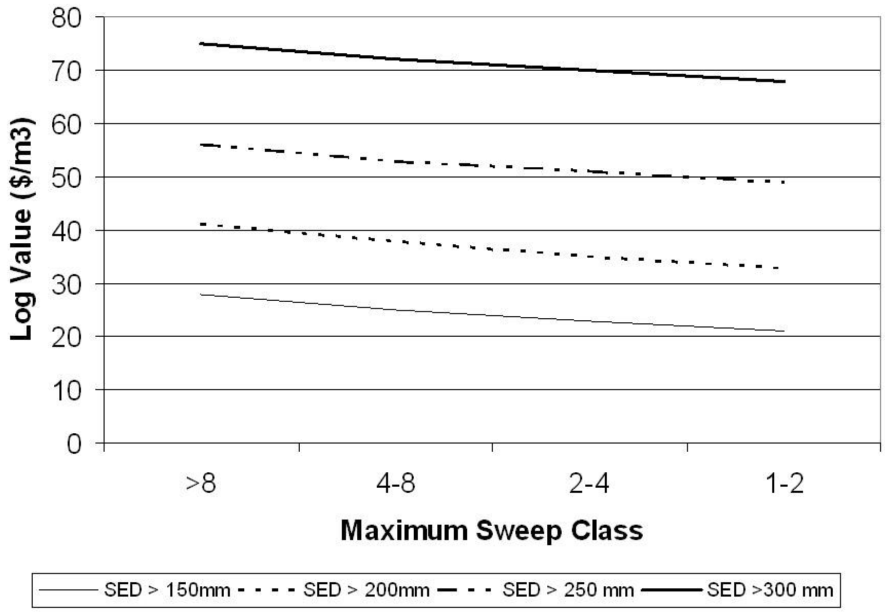

Figure 2: Relationship between log value ($\$/m^3$) and maximum sweep class; the higher the sweep class number the straighter the log.

Determining the impact of sweep on stand value

TLS can be used to determine sweep ratio in standing timber by measuring diameter and center-line displacement to the nearest millimeter, indicating the possibility of using this technology for assessing sweep in stand-level inventory in the future. To evaluate the impact of sweep on value we measured diameters, heights and sweep for the three plots used in this preliminary analysis using TLS in combination with the Treemetrics software. Log specifications and prices were assembled for chiplogs and sawlogs with different sweep classes. VALMAX Optimizer was used to convert the TLS data to volume and value estimates.

We found that, all other things being equal, not taking sweep into consideration would result in an overestimate of stand value by about $800 per hectare (~ 3% of stand value). A small amount of chiplog volume would be incorrectly assessed as sawlog material, but most of the overestimate would be due to an incorrect distribution of sawlog material into less sinuous classes.

As noted above, there have been few, if any, studies that have compared the accuracy of TLS scans with mill scans. Further comparisons between mill scan measurements and TLS scan measurements will reveal the level of accuracy of TLS sweep assessment. This will ultimately determine whether or not TLS technology could feasibly replace current methods of sweep determination in standing timber.

Increasing value with the addition of a veneer line

The mill being supplied from the poplar stands does not currently have a veneer line. The questions arose, “could more value be engineered into the supply chain by the possible addition of a veneer line to the mill?” Log specifications and prices were assembled for chiplogs, veneer logs, and sawlogs. Compared with sawlogs, veneer logs were shorter (1.3 to 2.5 m vs 2.6 to 3.8 m), straighter (maximum sweep allowed was SED/12 vs SED/8 to SED/1), and larger (minimum SED of 200 mm vs 150 mm). VALMAX Optimizer was again used to convert the TLS data to volume and value estimates.

Table 1: Comparison of value recovery before and after the simulated addition of a veneer line (Plots 2, 3 and 6 in Stand 1)

Plot	Total Volume (m^3/ha)	Total Value* ($/ha)	Value Difference ($/ha)	Sawlog (%)	Chip (%)	Veneer (%) (> 200 mm SED)
2	489	$20,910	$1,780	81	19	-
		$22,690		42	19	38
3	642	$30,730	$2,510	85	15	-
		$33,240		43	15	41
6	527	$19,740	$2,860	81	19	-
		$22,600		29	19	51
Average	549	$23,790	$2,390	82	18	-
		$26,180		38	18	43

* Note that total values are based on calculated return-to-log values for logs delivered to the mill-yard. Costs associated with harvesting and transporting logs have not been subtracted from these. Values may, or may not, reflect those obtained by GreenWood Resources.

Table 1 shows the potential value gained by GreenWood Resources though optimally allocating a portion of the sawlogs to veneer production. Preliminary results indicate that by adding a veneer line to the mill the value of the wood in plots 2, 3 and 6 increased by an average of $2400 per hectare. All of the veneer grade wood was projected to come from sawlogs, indicating that changing the allocation of a portion of the sawlogs to veneer production would increase the value of the wood in the stand studied. With further research there is potential for TLS to be used as a tool for predicting optimal product allocation, not only in poplar, but in many other species of standing timber.

Increasing value by changing trucking and/or mill infeed

As noted above, GreenWood Resources bucks all logs at the stump or landing to approximately 17 meters; primarily because 17 m is the maximum length that can be scanned in the mill but also to minimize handling and trucking costs. We determined the amount of sawlog volume that was lost due to bucking to 17 meters for these reasons. TLS and VALMAX were used to generate the percent of sawlogs lost from plots 2, 3 and 6 from this practice (Table 2). These preliminary results show that the percent of sawlog grade wood lost from bucking to 17 meters was significant for this stand. Depending on the value of the sawlogs lost, this could translate to significant value losses on an annual basis. Possible solutions could be to redesign the trucking and the front of the mill so that longer logs could be trucked and scanned.

Table 2: Percent sawlogs "lost" due to bucking to a 17 m rule (Plots 2, 3 and 6 in Stand 1)

Plot	Total number of sawlogs	Sawlogs lost	% Lost
2	90	8	8.9%
3	114	12	10.5%
6	116	10	8.6%
Average	107	10	9.3%

CONCLUSIONS

Although TLS is being used operationally in some parts of the world for assessing stand value and log product yields, it is in its infancy for many other parts of the world. Few studies have been carried out in hybrid poplar stands. No studies, that we are aware of, have compared mill scan measurements and TLS measurements.

Preliminary results from our study indicate that both the mill scans and TLS scans underestimated stem diameters; the underestimates being greater for the TLS scans. Elliptical stem diameters towards the base of the stem and nodal swelling in the first whorl above the pruned zone may have contributed to inaccuracies in TLS measurements. We believe that changes to software used to process the TLS data, which are currently underway, will address some of these issues. Capturing TLS data during the dormant season, when leaves have fallen, should also result in improved accuracy above the pruned zone.

The high level of detail on stem shape and sweep provided by TLS data, when combined with optimal bucking software, did allow us to evaluate the impacts of stem form on standing tree value. We were also able to assess the potential gains in value that could be obtained by altering practices in the forest (e.g. bucking to different log lengths for trucking) and in mill design (e.g. adding a veneer line or changing the mill scan infeed system).

We believe that TLS shows great promise as a tool for assessing stand value, determining the ability of a stand to meet market requirements, and designing value chain improvements. Analyses of the remaining 57 plots in our study, along with future research and development on TLS technology, will determine the rate at which this promise becomes reality.

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THE IMPACT OF BRUSH MATS ON FORWARDER SURFACE CONTACT PRESSURE

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ABSTRACT

During mechanized cut-to-length forest operations, forest biomass or brush (tree limbs, tops, and foliage) is placed as a covering layer (brush mat) on the surface of machine operating trails to improve trafficability. More recently brush has also been used as a source of renewable energy to offset carbon emissions from fossil fuels. However, these two uses are mutually exclusive; once brush is used on operating trails and mixed with mineral soil its calorific value is significantly reduced and can no longer be used as a bio fuel, while using brush solely for bio fuel will leave operating trails uncovered and result in severe soil disturbance. To manage the two competing uses of brush, the objective of this study was to quantify the impact of different brush mat amounts on machine surface contact pressure by placing these mats over a testing device and driving a forwarder on top of it. The testing device (load test platform) recorded the loading below the mats using high capacity load cells. In total, 20 test scenarios were performed with an 8-wheel forwarder to analyze differences in peak pressures recorded underneath brush mats of 5, 10, 15, 20, 25, and 30 kg m^{-2} each subjected to two, six, and 12 forwarding cycles. Results indicated a 24% lower average peak surface contact pressure underneath the 30 kg m^{-2} brush mat compared to when the machine was driven in direct contact with the load test platform.

Keywords: Biomass, brush, forest machinery, surface contact pressure, soil protection

INTRODUCTION

For the majority of the first half of the 20th century, anthropogenic disturbances on forest soils were quite low, both in frequency and magnitude, and were most often limited to the damages caused by horse traffic or sporadic uses of skidders. Nowadays, to be productive, efficient and safe, forest operations depend on heavy equipment to process and transport trees. Soil disturbances are predominantly associated with in-stand timber extraction processes when machines expose, compact and/or displace mineral soil while transporting timber from the felling site to a landing adjacent to a hauling road. The Canadian forest industry applies two main mechanized harvesting methods (cut-to-length, CTL; and full tree) to harvest and transport wood efficiently and safely from felling site to road side. The gross mass of machinery ranges from 10 to 40 metric tons and exerts nominal ground pressures of 60-180 kPa. This machinery operates directly on the forest floor, thus having the potential to cause severe soil disturbance (Nugent et al. 2003). The most frequent and depleting disturbance is soil compaction, which is defined as an increase in soil density (Craig 2004). By increasing a soil's mechanical resistance, the densification process can have a direct impact on plant growth through a reduction of air exchange and infiltration rate (Forristall and Gessel 1955, Froehlich and McNabb 1984, Corns 1988). Mechanized CTL operations usually require a harvester to fell and process trees and a forwarder to transport the logs from the machine operating trails to a landing accessible by trucks. When applying the CTL harvesting method, which dominates in Atlantic Canada, harvesting equipment travels on trails usually covered by harvest residues (limbs, tops and foliage of trees) resulting from the processing of harvested trees. This debris acts as a so called brush mat which helps to disperse machine loads over a greater area, thereby lowering peak loads exerted on forest soils and, as such, mitigates soil disturbances and related negative impacts on plant growth (Bettinger and Kellogg 1993, Richardson and Makkonen 1994). However, the high and volatile price of fossil fuels (oil and natural gas) combined with the need to reduce carbon emissions because of an apparent climate change, has focused interest of forest stakeholders in using harvest residues, such as limbs and tree tops, as a source of bioenergy.

A pre-requisite for any viable bioenergy operation is that brush be free of contaminants such as mineral soil, thus maintaining its full calorific value. To avoid such contamination, operators delimb trees on the side of machine operating trails to avoid any contact with the machine running gear and the forest floor, thereby eliminating the possibility of creating a brush mat to distribute the load (Eliasson 2005). With the absence of brush, a machine's surface contact pressure is directly and fully exerted to the ground, leading to potential increases in soil density and other disturbances. In short, brush used on machine operating trails for soil protection cannot be re-used for bioenergy generation and using all brush as bio fuel may cause severe soil disturbances along unprotected machine operating trails. In order to optimize the two competing uses of brush, knowledge of minimum quantities and qualities of brush for effective soil protection on machine operating trails is needed. With this knowledge, brush amounts necessary for soil protection could be allocated and the remaining brush utilized as bio fuel without compromising forest soil integrity along machine operating trails. The study attempts to provide necessary information in this respect by addressing the following objective.

Research objectives

1- Quantify the impact of brush mats on forest machinery surface contact pressure.

METHODOLOGY

Testing device

To measure and record dynamic loads exerted by forest machines, a load test platform composed of three separate sections, ramps, in- and out-feed, and load test platform itself was designed and constructed (Figure 1). The principal part of the structure was the load test platform measuring 4.09 m by 2.54 m for a total area of 10.4 m^2 and equipped with 24 high capacity (450 kN) load cells, each able to measure independent loads on a 30.5 x 30.5 cm resolution (size of a loading plate). In- and out-feed sections were built at the same height (19.4 cm) as the platform to permit testing at a zero percent gradient, thus avoiding potential wheel slip and a change in machine centre of gravity. Both in- and out-feed sections were of sufficient length to allow the full wheel base of the forwarder to be stopped without having any axle on the load test platform. Following a pass-over of both forwarder bogie axles over the load test platform, a period of no load (forwarder resting on in- or out-feed section) was necessary to allow load cells to decrease to a zero load, thus making it easier to differentiate between the various loading events. Depending on the required load resolution, load cells could be placed in different arrangements, in so called layouts, within the platform. Two load cell layouts (clustered and transect) were used during testing. To specifically quantify the impact of the forwarder, load cells were first positioned in a clustered pattern (4 clusters of 6 load cells each arranged in 2 adjacent rows of 3 load cells wide), directly located in forwarder tracks (Figure 1). This load cell layout offered the highest resolution to capture machine footprints. It was also of interest to understand how the brush could distribute applied loadings laterally. Therefore, load cells were also installed in a transect layout on two adjacent rows throughout the full width of the load test platform (12 load cells wide).

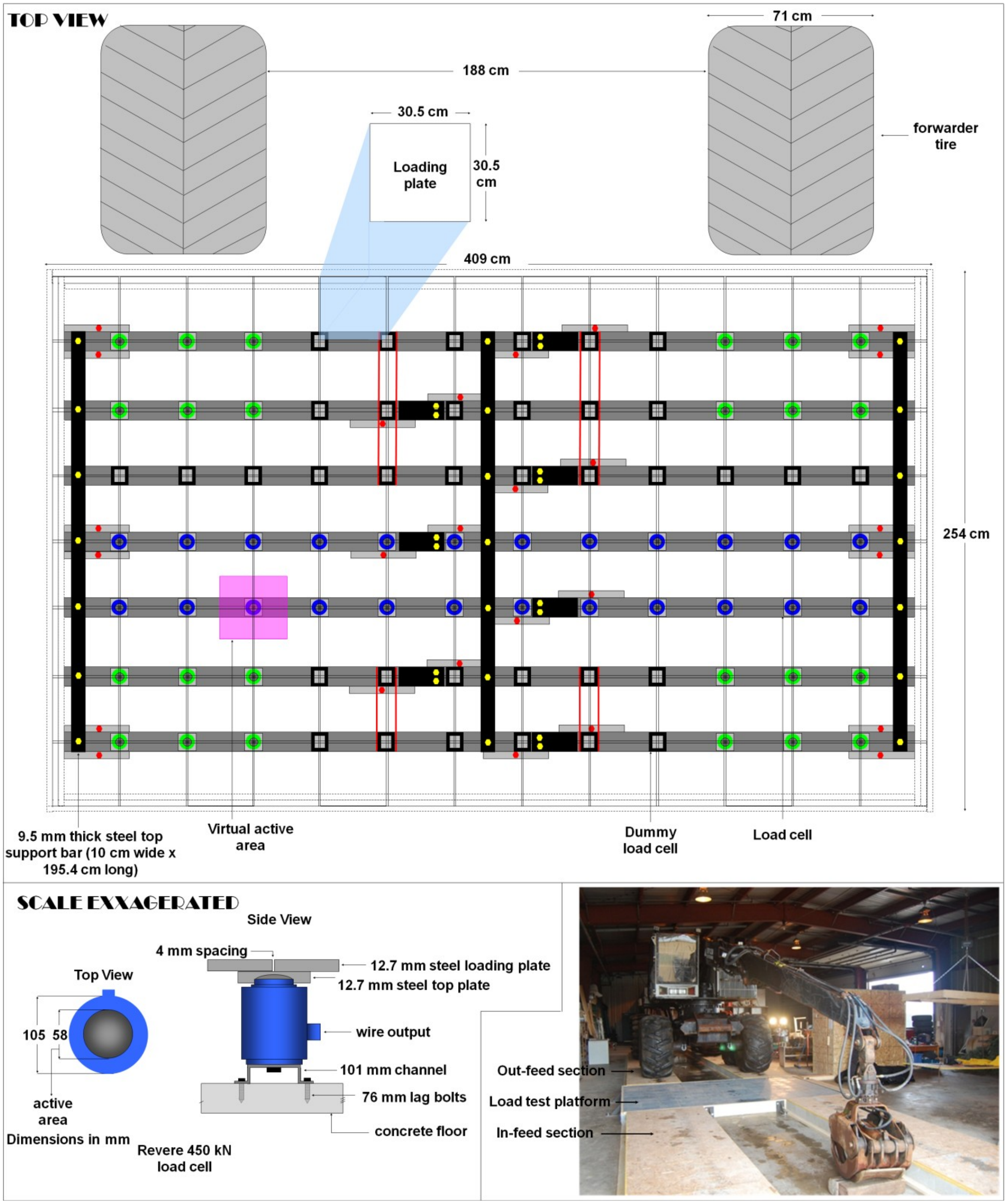

Figure 1: Schematic of load test platform. Green circles represent load cells placed in a clustered layout and blue circles show load cells positioned in the transect layout. Photograph illustrates the three fully assembled sections (in-feed, load test platform, and out-feed).

Forwarder specifications

A 2000 Timbco TF820-D forwarder with a tare mass of 23,500 kg and a load capacity of 20,000 kg was used for all tests (Table 1). This 8-wheel forwarder had two independent bogie axles. Olofsfors steel flexible tracks with widening plates, weighing 1,100 kg per unit, were installed on the rear bogie axle during all test scenarios. For better manoeuvrability over the load test platform and associated in-/out-feed sections, steel flexible tracks were not installed on the front bogie axle during testing. Based on the Pascal software (FPInnovations' ground pressure calculator), nominal surface contact pressure underneath the front rubber tired bogie axle was 67.7 kPa loaded and 64.5 kPa on the rear tracked loaded bogie axle. These surface contact pressures are based on a full load of 20 metric tons.

Table 1: Timbco TF-820D forwarder specifications.

Tare mass	Load capacity	Loaded mass	Nominal surface contact pressure: Front unloaded	Rear unloaded	Front loaded	Rear loaded	Tire size: Front axle	Rear axle
kg			kPa					
23,500	20,000	43,500	63.2	25.5	67.7	64.5	28L-26†	

† rear bogie axle equipped with Olofsfors Eco-track

Sampling procedure

Control parameters

To establish control parameters, the Timbco forwarder was first driven unloaded over and afterwards stopped on the bare load test platform (without brush cover). The resulting dynamic and static loads for each axle were recorded by the load cells and stored in a 25 channel data acquisition system. For data analysis, the loads (kN) recorded by each load cell were converted to surface contact pressure (kPa) by relating the recorded load to the area of the so called virtual active zone (930.3 cm^2, the size of a loading plate; Figure 1). The control test was replicated with the forwarder driven over the platform at the same position to verify the accuracy and precision of the load recording system. The same procedure was then repeated with the forwarder loaded with 6,680 kg of dry logs. Due to the extended time required to perform all tests scenarios, logs with relatively stable moisture content were chosen to limit mass fluctuations associated with varying log water content. As a result, we were not able to fill the log bunk to its full capacity of 20 metric tons before reaching its volume capacity.

Brush mat construction and forwarder traffic

After control parameters were assessed, actual testing with brush of varying quantity and quality was performed. Fresh softwood biomass (balsam fir and black spruce) imported from on-going CTL forest operations was stored inside the storage hall to reduce air drying and avoid further increase of moisture content due to precipitation. Prior to any brush amount test, branches used to create a brush mat were characterized individually by specie, diameter, and length. Aside from specie identification, branches were assigned to one out of four diameter classes ($x \leq 10$ mm, $10 < x < 30$ mm, $30 \leq x \leq 60$ mm, and $x > 60$ mm) and to one out of five length classes ($y \leq 1$ m, $1 < y < 2$ m, $2 \leq y \leq 3$ m, $3 < y < 4$ m, and $y \geq 4$ m). Following classification, branches were weighed with a digital scale and placed perpendicular to the direction of travel on the platform to simulate branch positioning of in-wood delimbing by a processor until the target brush amount (Table 2) was reached.

Table 2: Load test platform testing variables.

Testing surface type	Load cell layout	Target brush amount (kg m^{-2})†	Traffic frequency per test (cycles)	Replic. ‡
Brush in contact with loading plates	Clustered	5, 10, 15, 20, 25, 30	2, 6, 12	2
Brush in contact with loading plates	Clustered	10, 20, 30	2, 6, 12	0
Brush in contact with soil	Transect	10, 20, 30	2, 6, 12	2

† green mass
‡ replications

Once a brush mat was completed, the forwarder was driven over the brush covered platform unloaded and loaded at varying traffic frequencies per test (Table 2). Due to space limitations at the testing site, the empty forwarder was driven backwards (at a speed of 1.5 km h^{-1}) into the hall over ramps, in-feed section onto the platform and further on to the out-feed section until the front bogie axle was passed the platform. From there, the forwarder was driven at the same speed in a forward movement, again, onto the platform and in-feed section with ramps outside the hall. During this traffic, all 24 load cells had the potential to record dynamic loads. Afterwards, the forwarder was loaded with the same load as in control tests (6,680 kg) and driven over the platform in the same pattern. These two unloaded and two loaded passes over the brush mat constituted two forwarding cycles. Therefore, each cycle represented eight individual loadings (two loadings from each of the four forwarder wheels). For this project, 2, 6, and 12 forwarding cycles were studied to determine the capacity of the brush mat to attenuate surface contact pressure over repetitive loadings.

When all traffic frequencies were completed on a specific brush mat, the platform was cleared of the compressed brush and new brush, undamaged by machine running gear, was used for the next test. Replacing brush between tests was essential since the properties (strength, compressibility, yield point, etc.) of branches could have been altered by machine loadings. Due to branch size variation and potential moisture content differences, the six brush amounts (5, 10, 15, 20, 25, and 30 kg m^{-2}) tested over the steel covered platform with load cells placed in a clustered layout were replicated twice (Figure 2). Following theses tests, load cells were re-positioned into a transect layout over the full width of the platform to quantify the ability of a brush mat to distribute loadings laterally (Figure 2). With this transect layout, three brush amounts (10, 20, and 30 kg m^{-2}) were tested directly over the steel covered platform without replication to verify accuracy of the load cells in their new locations.

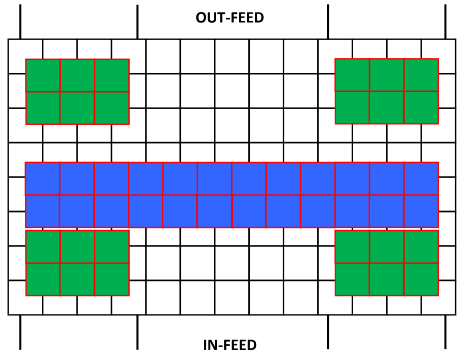

Figure 2: Schematic of clustered load cell layout identified by green virtual active zones and transect layout shown in blue virtual active zones.

After successful testing with the new load cell layout, brush mats of 10, 20, and 30 kg m^{-2} (each amount replicated twice) were tested on top of a 20 cm thick layer of mineral soil placed on the platform to obtain the response of the load cells under a flexible surface (Table 2). Prior to any tests, the soil layer located on the platform was compacted using a plate compactor for three minutes. The creation of brush mats on top of the soil layer and the forwarder traffic were performed the same way as for tests without soil layer described before. After all forwarder traffic cycles had been completed for a respective scenario, brush was removed from the platform and discarded and the soil was loosened with a shovel and re-compacted with the plate compactor before testing the next brush amount.

Statistical analyses

Statistical analyses were performed with SPSS and Minitab statistical software. Dependant variables were load or surface contact pressure readings obtained directly from the load cells e.g. peak surface contact pressure, sum of peak and second highest surface contact pressure, etc. To determine the impact of an independent variable (brush amount, log bunk load status (unloaded and loaded), forwarder traffic frequency, etc.) on the chosen dependant variable, a series of one way ANOVA's were performed and a probability level of 0.05 was chosen during all statistical tests.

RESULTS

Impact of brush on machine surface contact pressure

Due to the limited length permitted for this article, only results from the rear loaded axle will be presented. Furthermore, because the area of contact underneath a tire of the forwarder was greater than the surface area of one loading plate, total wheel load could not be completely captured by a single loading plate. Therefore, in order to adequately compare machine impacts, the sum of peak and the second highest surface contact pressures from an adjacent load cell will be presented.

When combining all replicas, loaded rear axle mean surface contact pressures recorded from the clustered load cell layout tests decreased from 311 kPa during the no brush (0 kg m^{-2}) scenario to

238 kPa for the 30 kg m^{-2} brush mat, equalling a 23.5% reduction in peak pressure (Figure 3A). Modifying load cell position from a clustered to a transect layout did not seem to have an impact as mean surface contact pressures decreased from 313 kPa with the no brush scenario to 236 kPa for the 30 kg m^{-2} brush mat, which translated to a 24.6% reduction (Figure 3B). As a reference point to brush amount in kg m^{-2}, pre impact average brush mat thickness was 20, 40, and 60 cm for the 10, 20, and 30 kg m^{-2} brush amounts, respectively. A statistical difference of mean surface contact pressure existed between 0 and 10 kg m^{-2} brush mats indicating a beneficial effect of having a minimum of 10 kg m^{-2} of brush to statistically lower machine surface contact pressure (Figure 3A-B). A further increase of brush also statistically lowered mean surface contact pressures up to the maximum brush amount studied of 30 kg m^{-2}.

Adding a soil layer on top of the steel platform lowered on average mean surface contact pressures by 25% in comparison to tests done directly over the steel covered platform (Figure 3C). The rear axle exerted lower mean sum of peak and 2nd highest surface contact pressures when it was in direct contact with the soil then when the platform was covered with 10 and 20 kg m^{-2} brush mats placed on top of the soil. This was a surprising result since we were expecting brush placed on top of the soil layer to further decrease mean surface contact pressures. However, upon further investigation we determined that the percentage of the 3rd highest average surface contact pressure to the sum of the four load cells wide (half cluster) was much higher when the machine was in direct contact with the soil than when brush was added. Therefore, combining all three highest surface contact pressures per loading (indicated with dashed lines in Figure 3C), showed a decrease of pressure from 270 kPa for no brush to 233 kPa for 30 kg m^{-2} brush amount.

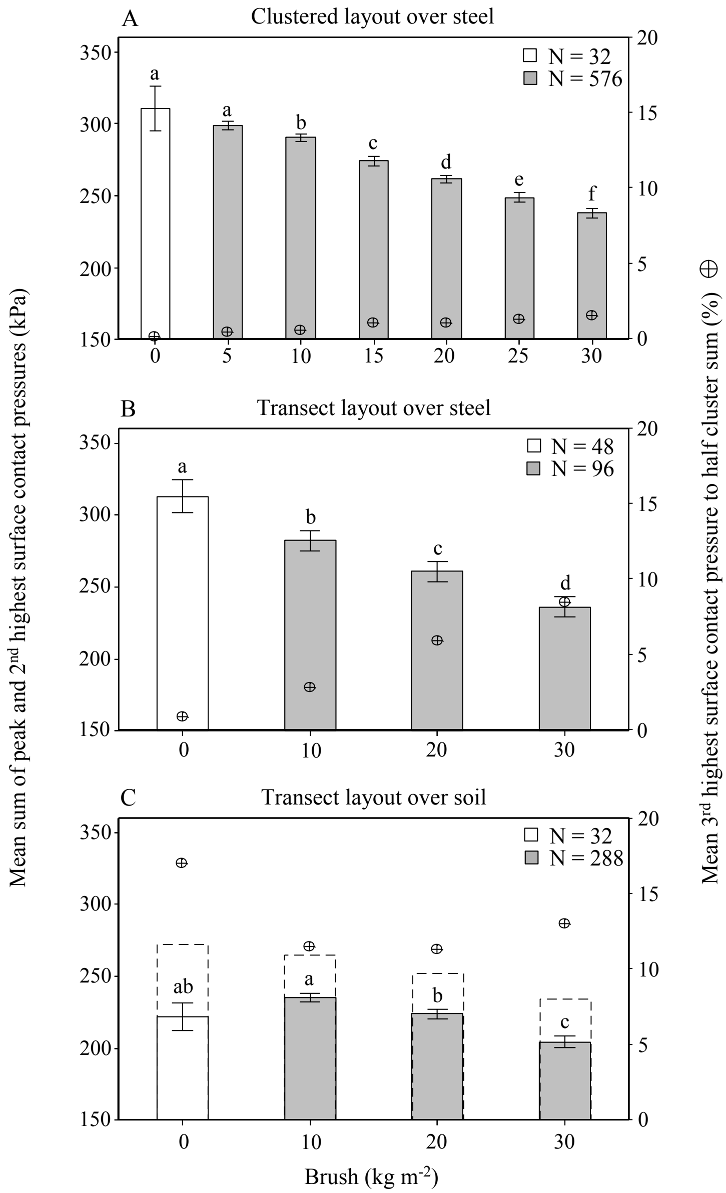

Figure 3: Mean sum of peak and 2nd highest surface contact pressures per brush amount (left ordinate). A different letter indicates a statistical difference at the 0.05 probability level. (Rear loaded axle only). Percent of mean 3rd highest surface contact pressure to the half cluster sum (right ordinate).

Impact of traffic frequency on the ability of brush mats to lower surface contact pressure

Results presented in Figure 3 combined loadings recorded from all traffic frequencies per test. To determine the ability of a brush mat to distribute loads over repetitive loadings, we averaged surface contact pressures readings recorded during 1-2, 3-6, and 7-12 loaded forwarder passes and identified them as 2, 6, and 12 passes in Figure 4. In the majority of cases, mean surface contact pressures slightly increased with an increase of traffic frequency and were more apparent as brush amount increased (Figure 4). There also seemed to be a larger difference of mean surface contact pressures between two and 12 loaded passes as brush amount increased from 15 to 30 kg m^{-2}.

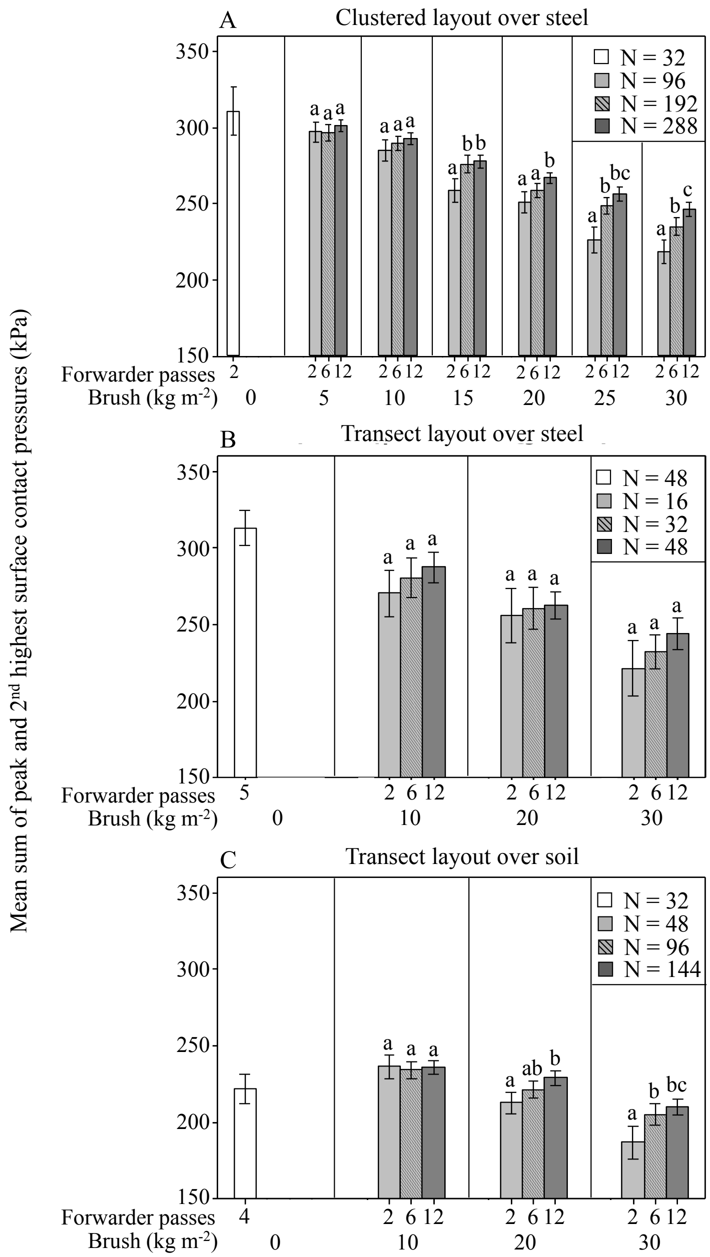

Figure 4: Mean sum of peak and 2nd highest surface contact pressures per brush amount and loaded forwarder passes. A different letter indicates a statistical difference at the 0.05 probability level per forwarder passes and brush amount. (Rear loaded axle only)

DISCUSSION

Impact of brush on machine surface contact pressure

Previous studies had focused on determining the impact of machine traffic over brush on soil physical conditions mainly through the assessment of soil mechanical resistance and density changes between pre- and post-impact measurements. Even though this study concentrated on surface contact pressure recorded underneath different brush amounts, our results offered similar trends to what was reported by Han et al, (2008) where a 15 kg m^{-2} brush mat statistically lowered penetration resistance on a soil of medium moisture condition at a 10 cm depth. Poltorak (2011) also reported benefits of using a 20 kg m^{-2} brush mat to statistically lower soil density increase (compaction) caused by mechanized forest operations compared to machine traffic directly over bare soil.

In both scenarios where brush was in direct contact with loading plates, an increase in brush amount lowered mean sum of peak and 2nd highest surface contact pressures. However, the same could not be concluded for the soil covered scenario since lower mean surface contact pressures were observed when the forwarder was driven directly over the soil compared to when the soil was covered with 10 and 20 kg m^{-2} of brush. We assume a reason for this to be the increased surface contact area between both track and tire to the soil in combination with the ability of a soil to distribute loads diagonally within the 19 cm thick soil horizon. However, expanding the zone of analyses from two to three load cells wide gave similar results (i.e. lower pressures as brush increased from 0 to 30 kg m^{-2}) as to when the forwarder was driven over steel rather than soil covered platform. The amount of brush required to protect forest soils is largely dependent on site characteristics (soil moisture, soil texture, organic content, stand type, etc.) and is therefore difficult to predict. However, based on the results obtained from the load test platform, we would recommend leaving a minimum brush layer of 10 to 15 kg m^{-2} on sensitive sites to lower machine surface contact pressure. Operating heavy equipment on highly susceptible soils (silty clay, clay at high water contents) could require the maximum brush amount tested of 30 kg m^{-2} or more depending on the number of passes required to extract the timber.

Impact of traffic frequency on the ability of brush mats to lower surface contact pressure

In forest operations, the frequency of off-road machine traffic is a function of harvested wood volume and its location throughout a cut block, and can vary between a single cycle to 12 cycles or more near a main landing where wood is being accumulated. For this reason it was of interest to quantify the response of a brush mat to lower machine surface contact pressure over repetitive loadings. The ability of a brush mat to lower machine surface contact pressure was reduced when traffic frequency increased from two to 12 loaded forwarder passes. As a brush mat was being compacted by repetitive loadings of the forwarder, branches were broken by the machine running gear which decreased the overall strength of the mattress. The difference between mean surface contact pressures recorded after two and 12 passes increased with increasing brush amount. This would mean that brush of higher amounts (20-30 kg m^{-2}) were more beneficial in reducing mean peak surface contact pressures at lower traffic frequencies. Nevertheless, these high brush amounts were still more suitable at distributing machine loads following 12 loaded passes than were the thinner 5 and 10 kg m^{-2} brush mats after just two passes.

CONCLUSIONS

This study attempted to quantify the impact of different brush amounts as a covering layer on machine surface contact pressure with the use of a load test platform. Brush mats >10 kg m^{-2} were proven to be beneficial in statistically reducing surface contact pressures of an 8-wheel forwarder compared to a no brush scenario. Furthermore, increasing traffic frequency from two to 12 passes caused brush mats to be slightly less efficient at distributing applied loads but remained beneficial at the highest traffic frequency tested. The competing uses of brush between acting as a mattress on trails to lower machine impacts and as a potential source of bio fuel for a clean source of energy will only get more severe with time. However, leaving brush on machine operating trails remains an essential and proactive method of mitigating soil disturbances during mechanized forest operations and needs to be an integral part of best management practices.

ACKNOWLEDGEMENTS

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EQUIPMENT MIX AND OPERATING STRATEGIES UTILIZED BY LOGGING BUSINESSES PRODUCING BIOMASS IN THE PIEDMONT OF VIRGINIA: PRELIMINARY RESULTS FROM A SURVEY OF BIOMASS PRODUCERS

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ABSTRACT

The southern Piedmont region of Virginia currently has a competitive market for biomass or "wood fuel" in addition to established markets for conventional roundwood products. This market includes an 80 MW wood fired electrical power plant which began operating in 1994 as well as two paper mills purchasing wood fuel to supplement energy production at their facilities. Logging businesses in this region have had the opportunity for over 15 years to adapt their harvesting operations to supply wood fuel along with conventional roundwood products. A mail survey of wood fuel producers in this established and competitive market was conducted to determine operating strategies and equipment utilized for producing wood fuel. The survey had a response rate of 52.2%. Results indicate that 96% of producers integrate wood fuel production into conventional roundwood harvesting operations. Most operations utilize a single loader for processing roundwood and wood fuel however 31% utilize multiple loaders with a single loader dedicated to wood fuel production. Eleven percent of operations utilize a strategy of rotating a single chipper among multiple logging crews. Wood fuel is produced using a chipper on 96% of operations and a grinder on 4% of operations. Seventy percent of chippers are disc style and 30% use drum style chippers. Operations tend to utilize older chippers with an average age of 12.7 years and a median of 600 horsepower.

INTRODUCTION

The Piedmont of Virginia currently has a competitive market for biomass or "wood fuel" in addition to markets for conventional forest products. The primary consumer in this wood fuel market is an 80 MW electrical power generation facility constructed in 1994 near Hurt, VA. In addition to electricity production, two paper mills also purchase wood fuel to supplement energy production at their manufacturing facilities. All three facilities (Figure 1) are located in the southern Piedmont region of Virginia.

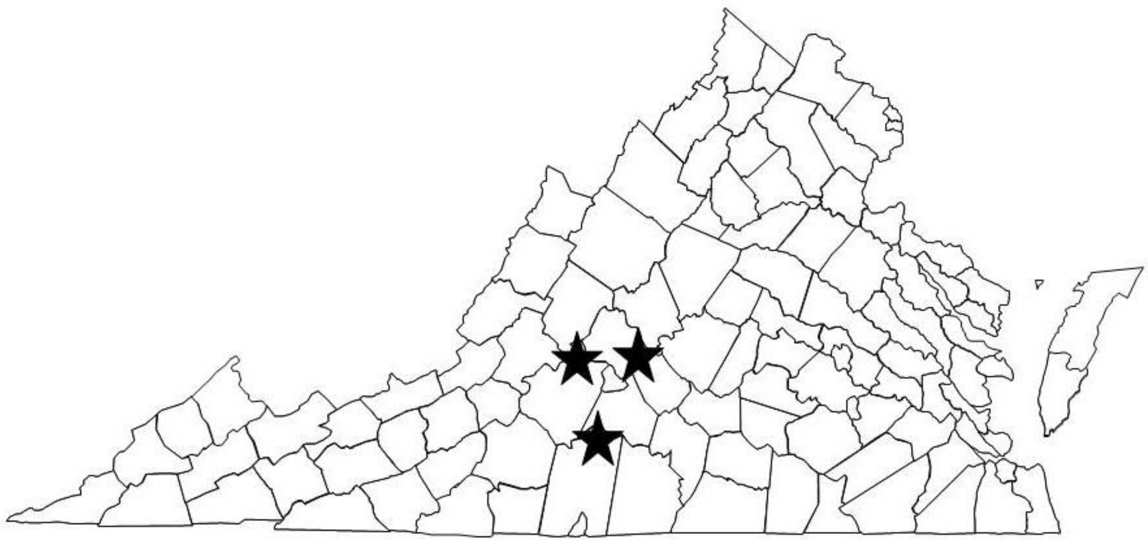

Figure 1: Location of study area's three wood fuel consuming facilities within the Piedmont region of Virginia.

Logging businesses in this area have had the opportunity for over 15 years to adapt their harvesting operations to meet the needs of this market for wood fuel along with conventional roundwood products. A previous survey of Virginia's logging business owners (Bolding et al. 2010) indicated that 16% of loggers in the Piedmont region used whole tree chippers to harvest logging residues. Further analysis of this logger survey data (Barrett et al. 2010) indicated that most of these loggers were using whole tree chippers to produce dirty chips almost exclusively on mechanized harvesting operations utilizing rubber tired feller bunchers and grapple skidders. However, this data did not include information on characteristics of the chippers or operating strategies for harvesting wood fuel.

Within an existing competitive market for wood fuel, one of the research objectives for this project is to determine the equipment mix and operating strategies utilized by logging businesses currently producing wood fuel in the piedmont of Virginia. This study utilized a mail survey to collect operational information from wood fuel producers. Similar studies have utilized field visits (Spinelli and Hartsough 2001) and a phone survey (Dirkswager et al. 2011) of biomass producers. Identifying operating strategies utilized by logging businesses producing wood fuel in this region could help logging businesses and forest managers understand the best strategies for integrating wood fuel harvesting into their operations if markets become available in other regions.

METHODS

Data collection was performed using a mail survey of current wood fuel producers delivering to biomass consuming facilities in the Piedmont of Virginia. The population consisted of wood fuel supplier lists provided by an electrical power plant and a paper mill. The mailing list included wood fuel suppliers who had delivered in-woods produced wood fuel in the past year. This list did not include suppliers of mill residues such as bark and sawdust. The combined mailing list included addresses for 94 wood fuel suppliers. A questionnaire was developed and mailed during November and December 2010 using a series of mailings modeled after the Dillman (2000) method.

RESULTS AND DISCUSSION

Response rate

Of the 94 questionnaires mailed to wood fuel producers, two were returned incomplete with an explanation that the survey did not apply to them. One producer was no longer in business and the other did not produce wood fuel from forest harvesting sites. After removing those, the adjusted population consisted of 92 wood fuel producer businesses. Forty eight questionnaires were returned for a response rate of 52.2 percent.

Operating strategies

Wood fuel production can occur either before, during, or after conventional roundwood harvesting. Ninety six percent of producers indicated that their wood fuel production normally occured during a roundwood harvesting operation with roundwood and wood fuel produced simultaneously. Integrating wood fuel production into a conventional harvesting operation requires some adjustments to in-woods operations. Sixty-five percent of operations simply added a chipper to the system and use a single loader for producing roundwood and wood fuel. In contrast, multiple loaders are utilized on 31 percent of operations with a loader dedicated to wood fuel production. Another 4 percent of respondents sometimes use both methods.

Some logging businesses with multiple crews have developed an operating strategy to better utilize the high production capacity of their chipper. These operations use one chipper to rotate among multiple logging crews. Utilizing this strategy allows the operation to accumulate material for chipping so that when the chipper arrives at the landing it can chip the accumulated wood plus chip wood brought to the landing while it is operating. This strategy of using a single chipper for multiple logging crews is utilized by 11 percent of wood fuel producers.

Equipment utilized for wood fuel production

Whole tree chippers are generally the preferred method for producing wood fuel with 96 percent of operations utilizing a chipper. Only two respondents indicated that they used a grinder and both indicated it was a tub grinder. One of the businesses using a grinder was primarily a land clearing operation and sometimes grinds logging residues. The other was a large multi crew operation.

For operations using a chipper to produce wood fuel, 70 percent indicated they used a disc style chipper while 30 percent used a drum style chipper. In addition to the style of chipper, producers were asked to provide information about other optional features of their chippers. Chippers with an infeed deck were utilized by 46 percent of operations (Table 1) and 23 percent of chippers had an attached loader. Six percent of operations indicated their chipper had a chain flail and presumably these operations would be capable of producing clean chips when using the flail and produce wood fuel without using the flail.

Table 1: Optional features of chippers used for wood fuel production.

Chipper options	n	Percent of chippers with option
Infeed deck	22	46
Attached loader	11	23
Chain-flail	3	6

Chipper manufacturers

Wood fuel producers reported using chippers from six different manufacturers (Table 2) with Morbark (47%) listed as the most common make of chipper. Horsepower reported for wood fuel chippers ranged from 150 to 950 horsepower. The median horsepower for each manufacturer ranged from 455 HP for Precision chippers to 750 HP for Trelan chippers. The median power for all wood fuel chippers is 600 horsepower.

Table 2: Wood fuel producer responses for make, horsepower, and age of chippers used to produce wood fuel in the Piedmont of Virginia.

		Horsepower			Age (yrs)		
Chipper Make	n	Min	Max	Median	Min	Max	Mean
Morbark	23	150	860	600	1	40	17
Trelan	9	550	800	750	5	17	10.3
Woodsman	6	250	950	650	1	5	2
Bandit	4	275	500	475	10	20	12.5
Precision	4	450	600	455	14	20	16.3
Dynamic	3	500	500	500	1	3	2
Overall	49	150	950	600	1	40	12.7

Results indicate that wood fuel chippers utilized on logging operations are relatively old. Ages ranged from a minimum of one year to a maximum of 40 years. Woodsman and Dynamic chippers had a mean age of two years, but these manufacturers represent only 18 percent of all chippers. The remaining makes of chippers are substantially older with mean ages ranging from 10.3 to 17 years. The relatively old age of chippers is likely influenced by markets and production levels of the wood fuel producers. The market for wood fuel in this region is variable and price can fluctuate considerably. When demand and price go down, many loggers will stop chipping production and leave logging residues in the woods until prices increase and it is profitable to harvest and transport again. The amount of wood fuel material available for chipping on a logging operation is generally relatively low compared to the chipping capacity of larger chippers so they tend to be idle much of the time. With the combination of cyclical demand and relatively low chipper utilization, many loggers have adopted the strategy of buying older chippers and investing less money than they would with newer chippers.

CONCLUSIONS

Within a competitive market for wood fuel, loggers in the Piedmont region of Virginia have been able to adapt their operations to produce an additional product. Loggers have primarily accomplished this through the addition of a chipper to their harvesting system and produce wood fuel during the conventional roundwood harvest. Most producers simply modified their system by adding a chipper to their landing. The majority of operations utilize older disc style chippers and operate with a single loader to handle roundwood and wood fuel. About one third of operations added a loader and utilize multiple loaders with one dedicated to wood fuel production. These producers have demonstrated that when competitive markets are available it is possible for a range of logging operations to successfully adapt their harvesting system to produce wood fuel along with conventional roundwood products.

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FASTTRUCK - A TRUCK SCHEDULING SYSTEM TO IMPROVE THE TRANSPORT EFFICIENCY OF IN-FIELD CHIPPING OPERATIONS

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ABSTRACT

An important problem in forest operations is the daily transport of logs or chips from different coupes being harvested, with known supplies, to destinations with their daily demands. The basic objective is to satisfy the demand for different products at each destination and maximize the utilisation of the harvesting equipment at each origin, while minimising transportation transportations costs and waiting times within technical, policy and labour constraints.

This paper presents the results of a trial of FastTRUCK, a truck scheduling system developed by the CRC for Forestry, to evaluate some of the factors that affect transport efficiency of Australian in-field chipping operations. The analysis focused on the effect of chipper productivity and utilisation, number of chipping operations accessible to each truck, truck loading and unloading time, net payload on daily transportation costs, number of trucks, and average truck utilisation. According to the results obtained payload and chipper utilisation are the major factors affecting transport costs. Potential savings of 52% and 29%, respectively, are possible to obtain with a better control and management of these factors.

Keywords: In-field wood chipping, simulated annealing, wood supply chain, transport efficiency

INTRODUCTION

Log transport by trucks constitutes a major part of the operational costs. It is therefore important to organise log and chip transport efficiently as trucks are expensive and operational costs are high. Many forestry transport managers are aware that their fleets could be better organised, perhaps with computer aided dispatching, routing and scheduling systems.

The main goal of routing and scheduling systems is to minimise transportation costs and waiting times within technical, policy and labour constraints. Vehicle routing problems (VRP) are difficult to solve and are unfit for timber transport vehicle routing problems (TTRVP) because the latter has many important features (Karanta et al. 2000). The closest problem class to TTRVP in the vehicle routing literature is freight pickup and delivery problems with time windows (Dumas et al. 1991). These problems shared many features but there are other elements that make

TTRVP a unique problem; for example, the pickup sites vary from day to day, there are strict time intervals to when a truck can enter an unloading (delivery) site, there are several type of timber and a given mill needs a specific type of timber, not all the truck can serve all pickup or delivery nodes, etc.

In-field wood chipping operations are common in Blue Gum (*Eucalyptus globulus*) plantation harvests across Australia. The harvesting systems typically consists of one feller buncher, one or two grapple skidders, and a delimber-debarker-chipper (DDC) (Figure 1). The system produces woodchips at the roadside in the forest and are particularly sensitive to planning and logistics because the DDC is not able to work unless a truck is on site to be loaded. The use of truck scheduling systems are valuable tools to evaluate the required level of receiving capacity at the woodchip terminal; very significant capital expenditure can be avoided based on the assessment of the required number of hydraulic dumpers (loading platforms) (Figure 1).

Figure 1: In-field chipping operation and woodchip terminal at port

The objective of this study was to evaluate some of the factors that affect transport efficiency of Australian in-field chipping operations. The analysis focused on the effect of chipper utilisation, number of chipping operations accessible to each truck, truck unloading time, and net payload on daily transportation costs, daily production, number of trucks, and average truck utilisation.

MATERIALS AND METHODS

FastTRUCK scheduling system

FastTRUCK is a windows-based system developed in Visual C++. It uses input from the existing parameters of the transport component of an operation and generates a range of alternatives to determine the optimal (or near optimal) operating scenario (Acuna 2011). The aim of the system is to minimise total transportation costs, and considers travel loaded and unloaded time, stood down time and fixed costs. To determine optimal schedules, FastTRUCK requires different input parameters (Table 1).

Table 1: Inputs required by FastTRUCK

Trucks	Dumpers	Chippers	Routing options
1. Min and Max time per shift 2. Speed empty and loaded 3. Truck payload 4. Cost travel loaded and unloaded 5. Cost stood down and fixed cost	1. Number of dumpers available 2. Starting and ending working time 3. Capacity (trucks/hr)	1. Number of chippers available 2. Starting and ending working time 3. Loading time 4. Productive time out of scheduled time	1. Multiple destinations by truck 2. One destination by truck 3. Two or three destinations by truck (clusters)

As output, FastTRUCK reports the optimal number of trucks required for the operation, total transportation cost, total volume of chips hauled to dumpers, average truck utilisation, average truck waiting time and average loaded running percentage (travel loaded /total travel distance). Detailed results by truck are exported to Microsoft Excel® and include total time, total cost, trips to dumpers, waiting time, utilisation, running loaded percentage, arrival times at forests and dumpers, and optimal schedule for one day.

Simulated annealing algorithm

Optimal truck schedules are created by FastTRUCK using a simulator and a simulated annealing algorithm. The simulator produces truck schedules and allow the system to calculate metrics such as total time, waiting time and total cost. Simulated annealing is a meta-heuristic whose approach is similar to the random descent method in that the neighbourhood is sampled at random. It differs in that it is possible to escape from being trapped at a local optimum by accepting worse solutions, with a small probability, during its search iterations (Reeves 1993).

Parameters for analysis

In the case scenario, the following parameters were used for the analysis:

- **Trucks:**
  - 82.5 t GVM road trains (50 t payload)
  - Truck working shift limit: 6 h minimum to 12 h maximum
  - Average road speed 75 km/h empty and 65 km/h loaded
  - Annual freight task of 900,000 tonnes
  - Centrally dispatched fleet (any truck can go to any chipper)
  - Average haulage distance of 72 km with lower and upper lead distance of 29 and 150 km respectively

- **Infield chippers:**
  - ❖ 8 active harvest operations on single 10 h shift
  - ❖ Loading time 60 min per truck
  - ❖ Chipper utilisation 90%
- **Receiving facility:**
  - ❖ One facility with two dumpers
  - ❖ Capacity per dumper of 250 gross metric tonnes per hour (unload up to 5 trucks per hour)
  - ❖ Facility open 14 h per day

A sensitivity analysis was conducted to determine the impact of chipper productivity and utilisation, number of chipping operations accessible to each truck (routing option), truck loading and unloading time, and net payload on four performance metrics: 1. Fleet size, 2. Daily production (tonnes), 3. Average truck utilisation (%), and 4. Transportation cost ($/tonne). In addition, total cost savings for an annual freight task of 900,00 tonnes were calculated by operational factor.

RESULTS AND DISCUSSION

Impact of reduced chipper utilisation

Table 2 shows the effect of reduced chipper utilisation. In each case the chipper was scheduled for 10 hours. There is a significant increase in the number of trucks (29%) when the chipper utilisation is increased from 75% to 90%. This is a consequence of the productive working times associated, which are 450 min (7 truck arrivals), 510 min (8 truck arrivals), and 540 min (9 truck arrivals), for a chipper utilisation of 75%, 85%, and 90%, respectively. The increased number of arrivals with 90% chipper utilisation has a substantial impact on the number of trucks required for the operation, which in turn increases the transport cost per tonne. However, savings of around $1/tonne are expected for the chipper when its utilisation increases from 75% to 90%.

Table 2: Effect of chipper utilisation

Performance metrics	Chipper utilisation		
	75%	85%	90%*
Fleet size (number of trucks)	20	24	28
Unit cost ($/tonne)	9.49	9.71	9.90
Daily production (tonnes)	2,800	3,200	3,600
Average truck utilisation (%)	88.3	87.6	86.4

*Control scenario

Impact of increased dispatching restrictions

Table 3 shows the effect of restricting the number of in-field chipping operations an individual truck can service. There is a 7% reduction in the number of trucks required for the operation when multiple chipping operations are available to service. Given that the two dumpers are in the same geographical location, the running loaded percentage is always 50% and there is no possibilities for backhauling. Thus, the transport cost reduction attributed to multiple destinations is only 3%.

Table 3: Effect of the number of operations available to service by each truck

Performance metrics	Number of in-field chipping operations available to service		
	1	2	Multiple*
Fleet size (number of trucks)	30	29	28
Unit cost ($/tonne)	10.16	10.03	9.90
Daily production (tonnes)	3,600	3,600	3,600
Average truck utilisation (%)	87.9	87.0	86.4

* Control scenario

Impact of increased loading times

Table 4 shows the effect of loading time. Increasing the loading time from 50 min/truck to 60 min/truck results in an increased cost of $0.39. A further rise in loading time from 60 min/truck to 70 min/truck results in a reduced cost per tonne (compared to 60 min loading time) due to the substantial reduction in the fleet size. Loading time has also a direct effect on the number of daily truck arrivals (10 with 50 min/truck, 9 with 60 min/truck, and 7 with 70 min/truck) and number of trucks required for the operation. Consequently, the daily production is reduced by 30% when loading time increases from 50 min/truck to 70 min/truck.

Table 4: Effect of loading time

Performance metrics	**Loading time**		
	50 min/truck	60 min/truck*	70 min/truck
Fleet size (number of trucks)	29	28	21
Unit cost ($/tonne)	9.54	9.90	9.73
Daily production (tonnes)	4,000	3,600	2,800
Average truck utilisation (%)	87.7	86.4	88.2

* Control scenario

Impact of payload

Table 5 shows the effect of net payload. Assuming the same loading time, there is no major effect on fleet size when net payload increases from 47 to 53 tonnes/truck. If that is not the case, the advantages of hauling bigger payloads might be offset by the extra time required to load the trucks. Increasing payload from 47 to 53 tonnes has the biggest single impact on transport cost per tonne (more than $1.1/tonne) and daily production (432 tonnes).

Table 5: Effect of net payload

Performance metrics	**Net payload**		
	47 tonnes/truck	50 tonnes/truck*	53 tonnes/truck
Fleet size (number of trucks)	28	28	28
Unit cost ($/tonne)	10.53	9.90	9.34
Daily production (tonnes)	3,384	3,600	3,816
Average truck utilisation (%)	86.4	86.4	86.4

* Control scenario

Annual cost savings

Figure 2 shows the annual savings for an annual freight task of 900,000 tonnes which corresponds to the volume hauled by one of the forest companies in Western Australia. The total savings resulting from a better control of the operational factor assessed in this study are in excess of 2 million dollars. More than 50% of these savings are explained by an increase in payload. Increasing the payload from 47 tonnes to 53 tonnes results in a reduction in transport costs of $1.2 per tonne or $1,080,000 per year for an annual volume of 900,000 t. These results are consistent with those obtained in previous studies carried out by the CRC for Forestry (Brown 2008). The second major operational factor is chipper utilisation. Increasing chipper utilisation from 75% to 90% represents a slight increase in transport cost of 4%, but also results in a drop in the chipping cost through improved chipper utilisation. Through increased chipper utilisation is it estimated that an overall saving of approximately $600 000 can be made annually for the operation presented in the example.

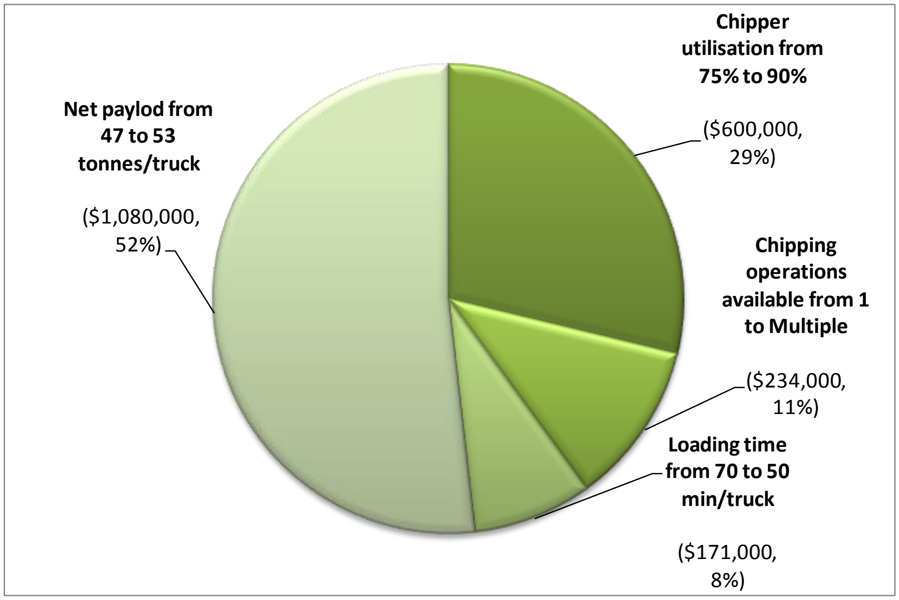

Figure 2: Annual savings for a freight task of 900 000 tonnes

CONCLUSIONS

- The impact of operational factors on transport costs and opportunities for improvements can be determined by using optimal scheduling systems such as FastTRUCK.
- Large savings in transport costs are possible without a major shift in technology by optimising truck schedules, maximising payload and improving the efficiency of chipping operations.
- Payload and chipper utilisation are the major factors affecting transport costs. Control and improvement of these factors accounted for 52% and 29% (respectively) of the potential savings obtained.

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Assessing the Effectiveness of Forest Soil Tillage Practices

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ABSTRACT

Numerous ground-engaging teeth, disks, and shanks of forestry equipment are used to till forest soils. The effectiveness of these practices to loosen soil has less frequently been reported, and the methods used are often time consuming and expensive. Methods of measuring soil to assess tillage effectiveness will be briefly reviewed and a new method that is easy to use in the field will be presented. Effective soil tillage loosens soil and increases the elevation of the soil surface; the new method measures the change in soil elevation before and after tillage using a rotating laser level, permanent reference points, and temporary transects. The method was used while testing equipment options for tilling temporary forest soils and oil and gas wellsites in Alberta. Plowing soil to depths of between 0.7 and 0.9 m consistently produced gains of soil elevation that averaged 0.15 m immediately following tillage, and was more effective than rippers. After four years, about 30 percent of the gain in elevation was still measureable, which produces 4 to 5 cm of increased air-filled porosity and/or increased water holding capacity. Soil cores confirmed that the tillage increased soil water content and increased air-filled porosity. Measuring the gain in soil elevation is a practical method of assessing the effectiveness of tillage in the field and reinforces the need for tillage practices to produce large increased in soil elevation if tillage practices are to be effective.

INTRODUCTION

The effects that equipment used to harvest forests and transport logs has on soil and future forest productivity have been a concern for several decades (Froehlich and McNabb 1984). Reducing the ground pressure of skidding equipment with wider tires and tracks have been one method used with some success (Froehlich et al. 1981), but these machines can still cause significant compaction when the soil is wet (McNabb et al. 2001). Limiting machines to dedicated skid trails is also an effective option to limit the areal extent of the soil impact but is a less useful practice on wet soils of low strength that are more easily rutted.

The soil in temporary roads needed to access logs within cutblocks or a series of cutblocks are more severely impacted by truck traffic than the soil impacted by skidding logs. In western Alberta, logging trucks can compact soils to soil densities equal to the maximum densities measured in laboratory compaction (Proctor) tests (McNabb 1994). Furthermore, the impact to soil can change soil porosity and water retention properties of the soil to a depth of at least 0.6 m (McNabb 1997). Within this layer of soil the impact is severe enough to destroy soil structure and create massive soil. This damage of soil structure causes numerous changes to soil physical properties that can affect the growth of the trees (Froehlich and McNabb 1984), as well as severely mpair the hydrologic function of the soil profile and adjacent area.

When soil impacts can not be avoided or minimized, the soil is commonly tilled. Most tillage is done with dozers and excavators using conventional ground-engaging attachments, or their modifications. As a result a wide range of teeth, shank spacing, and tooth modifications are used by companies to till soil. As an alternative, site preparation equipment is sometimes used but the depth of tillage is generally shallow (Gent et al. 1984). Only three-shank, winged-subsoiler has been specifically developed for tillage of forest soils (Davies 1990), but is less effective in soils of higher clay content (McNabb 1994). The effectiveness of many of these implements used in forests for restoring the soil physical environment has not been reported (Sutherland and Gillies, 2001). Measuring the effectiveness requires access to expensive equipment and is generally time consuming (Andrus and Froehlich 1983, McNabb and Hobbs 1989, Davies 1990, McNabb 1994). Furthermore, some of the commonly used methods of measuring soil may not be as reliable when used in tilled soil. There remains a need for simple and effective methods for assessing the effectiveness of tillage quickly in the field (Bulmer 1998).

The objective of this paper are two-fold: briefly review the methods that have been used to measure the effectiveness of tilled soil; and report on a new field method of assessing the effectiveness of soil tillage that is simple and fast. The field method has been used for several years in Alberta to evaluate deep tillage of oil and gas wellsites and forest roads in Alberta. The method will also be used to confirm the sustained benefits of the deep tillage after 4 years, and was verified with the measurement of soil density, water retention, and air-filled porosity on soil cores.

COMMON MEASURES OF TILLAGE EFFECTIVENESS

Assessing the effectiveness of a tillage operation is difficult. Tillage loosens the soil, but some of the increased porosity is lost over time by the natural consolidation of the soil. From a loosen state, a soil will consolidate toward a normal, or stable, bulk density (Heinonen 1977). In the absence of vehicle trafficking, how long it takes to achieve this density is unknown, but the number of cycles of freezing and thawing, wetting and drying, and the amount of precipitation are important contributing factors. The normal bulk density of tilled soil is also likely to be less than that of undisturbed soil. Therefore, sampling loose, tilled soil, and disturbances of the soil in the process of collecting a sample, will affect the reliability of most of the methods of measuring tillage effectiveness.

Soil Density and Penetrometers

Soil density can be measured using undisturbed soil cores or soil density gauges; however, the loose soil makes obtaining undisturbed soil cores nearly impossible immediately after tillage. The collection of soil cores with the more commonly used, thick-walled samplers that are hammered into the soil will compact tilled soil and affect the measurement of soil density and porosity. Therefore, a high priority must be placed on verifying the quality of each core collected. The highest quality, soil cores are generally collected in thin-walled rings that have not been hammered into the soil (McNabb and Boersma 1993), but in recently tilled soil this method will not guarantee the soil cores are undisturbed.

Two-probe soil density gauges have been used to measure soil density following ripping of a forest site in southwest Oregon (McNabb and Hobbs 1989); however, these gauges are limited to a depth of 0.3 to 0.6 m. When oriented in the direction of tillage, a two-probe gauge can provide an accurate assessment of the tillage effect around a single tooth or tine (Figure 1).

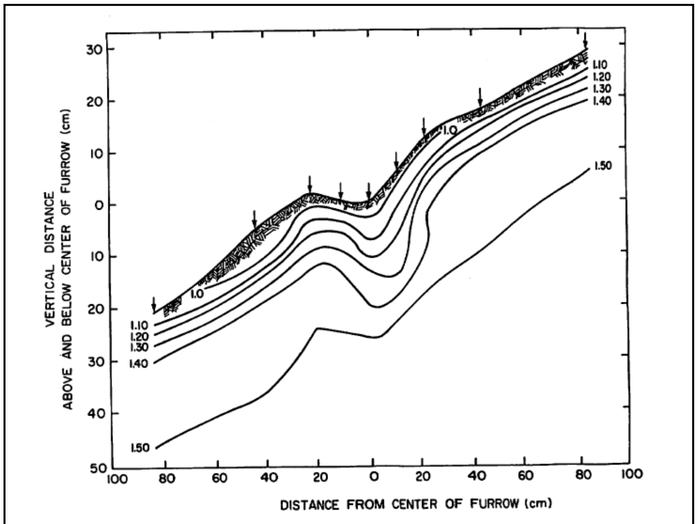

Figure 1. . Cross-sectional profile with isolines of soil bulk density following tillage with a single, tine ripper. The soil is a Typic Haploxeralf and located in southwest Oregon. The arrows mark points were a dual-probe gamma gauge was used to measure soil density parallel to the furrow at 5 cm depth increments (8 replications). (Source: McNabb and Hobbs 1989).

Penetrometers are commonly used to access tillage effectiveness, whether it is simply a rod pushed into the ground or a more sophisticated unit that records penetration resistance according to the depth. These units are compatible with deep tillage operations (Dunker et al. 1995, Baumhardt et al. 2008). As with any application of a soil penetrometer, and in tilled soil maybe more so, soil penetrometers require considerable expertise in their use and interpretation because of the confounding interaction of soil density, soil water content, depth of measurement, and amount of fracturing of the soil by the tillage operation.

Size of Clods

Size of clods produced by a tillage operation can be used as a measure of tillage effectiveness (McNabb 1994, Dexter and Birkas 2007, Kzric et al. 2009). Dexter and Birkas used a portion of clods larger than a certain size to access the effectiveness of seedbed tillage practices, while Kzric et al. use the maximum size of clod produced to establish different tillage treatments in a forest landing restoration project in British Columbia, Canada. McNabb used a clod size distribution curve of a percentage of material passing different screen sizes as a measure of tillage effectiveness in a forest road reclamation project in Alberta, Canada (Figure 2). Clod size distribution can also be used to calculate packing, or gradation, parameters for tilled soil that may have value in assessing seedbed quality. Clod sizes can be determined in the field using a rock screening set, which commonly uses a set of screens with a grid between 0.005 to 0.076 m, and a field scale. Large samples are needed to minimize the risk that the excavation of the sample is not reducing clod size.

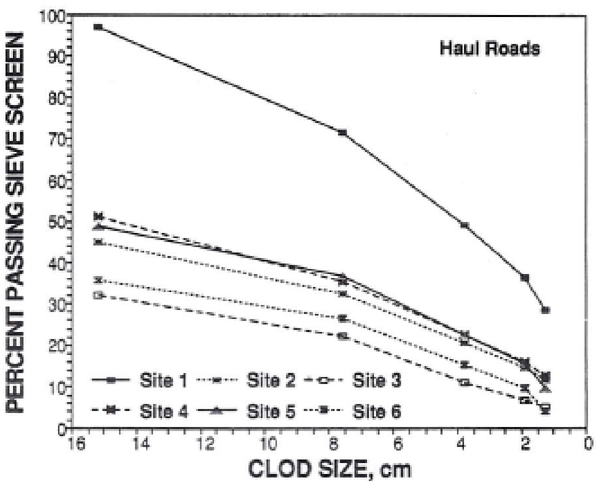

Figure 2. Clod size distribution of soil from the 0-30 cm depth of forestry haul roads and landings tilled with the forestry subsoiler (Figure 2). Soils were the subsoil horizons with mostly clay loam and clay textures, and located in west-central Alberta, Canada. Each point on a line corresponds to the size of the grid used to sieve the sample. (Source: McNabb 1994).

Excavated Profile

Trenches can be excavated across tillage furrows to expose a cross-section of the tilled soil (Andrus and Froehlich 1983, Raper 2005). Careful separation of the loosened soil from the untilled soil will define the boundary between the two materials. It is important to maintain reference points on either side of the furrow so that the original surface of the soil is known, and measured prior to tillage. Measurement of the elevation of the surface and the boundary of the tilled/untilled soil can be graphed to illustrate the area of soil loosened by tillage.

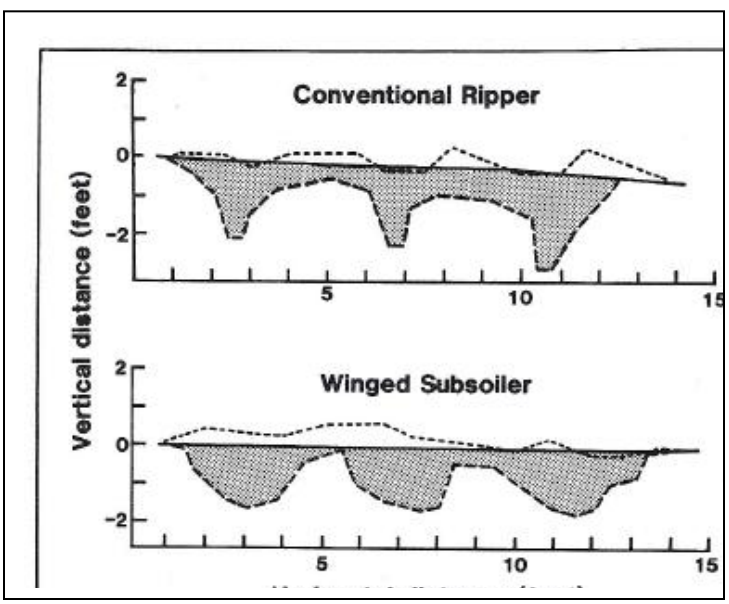

Figure 3. Excavated cross-section of furrows created with three, conventional rippers or winged subsoilers. The research was done in western Oregon but the soil type and wetness were not identified. (Source: Andrus and Froehlich 1983).

NEW FIELD METHOD OF ASSESSING TILLAGE EFFECTIVENESS

Method

A new method of measuring tillage effectiveness, and deep tillage practices in particular, has been used in Alberta for several years. The methods involves measuring soil elevations along transects established across an area prior to tillage and remeasuring the elevations at the same points afterwards. A similar method has been used to measure soil lift from tillage in mined lands in Australia by Croton and Ainsworth (2007).

The method is based on the principle that effective soil tillage fractures and loosens the soil thereby increasing soil porosity. Soil porosity can only increase if the soil volume increases. In the field, lateral confinement of soil limits volume expansion to the vertical axis. Therefore, any tillage induced increase in soil porosity must increase the elevation of the soil surface. Soil elevations can easily be measured in the field before and after tillage to calculate a gain in soil elevation.

Figure 3 is a general example of the relationship between a decrease in soil density as a result of increasing soil porosity and the gain in soil elevation for different average depths of tillage. An important point that this graph illustrates is that for tillage below a depth of depth of about 0.3 m, relatively large differences in the average elevation of the soil surface is required to produce small decreases in soil density. The measurement provides a single value for the increase in soil porosity and decrease in soil density produced by tillage; it does not provide a measure of where in the soil profile the porosity is located. Tilling plots of the same soil at increasing depths could provide some insight as to the effectiveness of a tillage practice at different depths, but would need to be interpreted carefully.

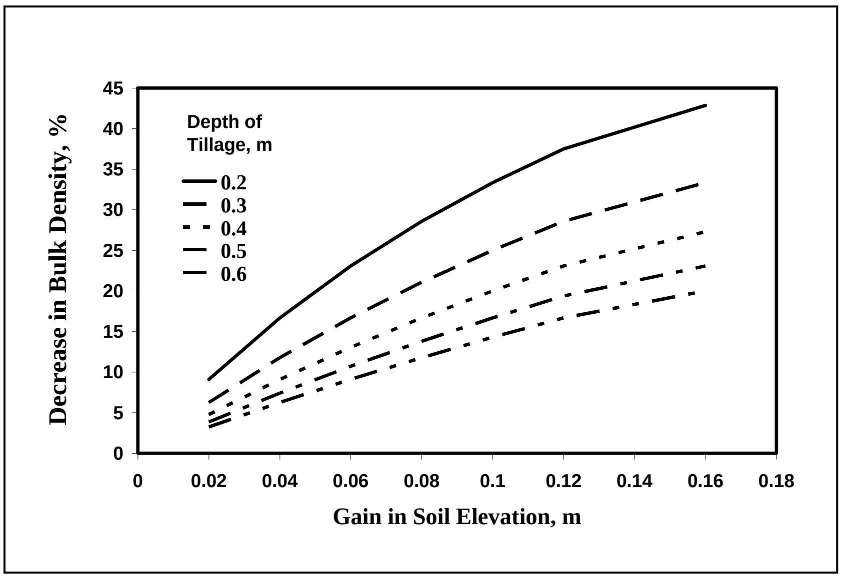

Figure 3. General relationship between the gain in soil elevation as a function of the depth of tillage and the decrease in soil bulk density. The assumptions are the average soil density for the soil profile is 1.30 Mg/m^3, all soil is fractured to the depth listed, and the fracturing is uniform for each depth.

The gain in soil elevation can be measured with a rotating laser level and rod by taking measurements from a permanent reference point and reestablished transects across tilled soil. Two methods of establishing transects for the measured of the gain in soil elevation have been used in Alberta. Both methods require a reference point that can not be disturbed by tillage for measuring all elevations. On narrow linear disturbances such as forest roads, the reference point can be a stump several meters from the road. When used to measure tillage of wellsites, an area was left untilled and the reference point marked with a rebar.

A moderately priced, laser level commonly used in the home construction industry can have an accuracy of ±0.005 m at a distance of 30 m. Reestablishment of transects in this application found the lasers had an average accuracy of about 0.003 m for distances between 4 and 20 m. All the best management practices for using a rod and level apply in this application.

On temporary roads, four transects were installed diagonally across the road with the end points marked off the road so that they would not be damaged by the equipment tilling the road. The angle that the transect made with the road varied but the transects were installed so that there were at least 10 measurements points, 1 m apart, taken along each transect on the section of the road to be tilled. Four transects were installed on each road segment measured for a total of 40 elevations.

On wellsites (approximately a square 110 m on a side), the reference point was a common end point for four transects radiating away from the point in four directions. The opposite end of each transect was in tilled soil about 15 m away. It was located by azimuth of a line between the reference point and a permanent object around the perimeter of the wellsite, such as a single tree, so that it could be more easily and accurately relocated to measure soil elevations after the soil was tilled. Soil close to the reference point was not tilled and 10 measurements, 1 m apart, were taken along each transect with the first measurement taken at between 3 to 5 m.

Results

The gain in soil elevation has been used to assess the effectiveness of different tillage implements on forest roads and wellsites in Alberta. The gain in soil elevation was always measured immediately following tillage, when the soil is most porous. Four wellsites were remeasured four years after tillage and provides a more sustainable measure of the longer term benefits of the tillage.

Temporary summer roads in several cutblocks on Luvic Gleysols in north-central Alberta were tilled with a Caterpillar® D7G with two standard rippers, or a pair of prototype RipPlows specifically designed for deep tillage with dozers (Figure 4). The road was tilled with lapping passes so that the main traffic area was tilled with a shank spacing of approximately 1 m. Rippers operated at a depth of about 0.7 m, and the RipPlows at a depth between 0.4 and 0.5 m; the older dozer was under powered for pulling RipPlows deeper in the compacted, higher clay content soils. For tree replications, rippers produced a gain in soil elevation of 5.8 cm, and the RipPlow a gain in soil elevation of 13.0 cm.

Figure 4. Pair of prototype RipPlows on a Caterpillar® D7R used to till forest roads and wellsites in Alberta. Soil can be tilled to depths up to 0.90 m and produce a gain in soil elevation of 0.15 m.

Numerous wellsites in northwest Alberta have been tilled with the RipPlows pulled with Caterpillar® D7Rs, which are capable of plowing the soil to depths of between 0.8 and 0.9 m (Figure 4). With lapping passes, the RipPlows cover over 65 percent of the area. In this practice, RipPlows consistently achieved a gain in soil elevation of 15 cm; the soils were mostly Orthic Grey Luvisols and Luvic Gleysols. After four years, the transects on four sites were reestablished and the soil elevations remeasured. About 30 percent of the original gain in soil elevation remained. This represents about a 4 to 5 cm increase in soil porosity that is allocated to increasing soil aeration and/or soil water holding capacity. Undisturbed soil cores were collected at one wellsite at a depth of 30 cm and the tillage significantly increased volumetric water content of the soil and air-filled porosity. Natural consolidation of the soil over time causes the decrease soil elevations and an evolution toward a normal soil bulk density (Heinenon 1977). After four years, the improved soil porosity may be sustainable for some time; in the absence of heavy trafficking, the benefits of deep tillage can persist for at least three decades (Baumhardt et al. 2008).

OPERATIONAL CONSIDERATIONS

All effective tillage practices will create a loose, unstable soil that will consolidate over time, and shift the soil toward a normal soil bulk density. The time period could be relatively short for shallow tillage but is generally longer for deeper tillage. Intentional and unintentional trafficking of soil after tillage will also significantly reduce soil porosity. In Alberta, a single pass by a tracked log loader over a recently tilled, logging road reduced the gain in soil elevation in the tracks by over 50 percent, and about 35 percent between the tracks. Therefore, the method chosen to evaluate tillage effectiveness must consider how the date are to be used and whether the method will affect the data.

If the objective is to assess the effect of tillage on soil density, soil water retention, and aeration status of the soil, the sampling of undisturbed soil should be delayed until most of the consolidation is complete. Collection of undisturbed soil cores from recently tilled soil is improbable immediately after tillage. Thick-walled core samples, particularly if hammer driven into the soil will compact the soil in the process. The quality of the cores can be assessed by removing the top of the sampler and comparing the elevation of the soil inside the ring with the soil outside the ring; the elevation of a minimally disturbed sample should be the same. The use of thinned-walled engineering samplers has been found to the best when gently pushed into the soil by hand. Methods of collecting undisturbed soil cores in weak soils have been described in McNabb 1993, McNabb et al. (2001). One- and two-probe soil density gauges cause the least disturbance and the two-probe gauges are more accurate but not very common.

The measurement of clod sizes, which can be readily done in the field with field sieve sets and scales is well suited for assessing the quality of surface soil as a seedbed. Large samples are needed to reduce fracturing clods during excavation (McNabb 1994). Obtaining quality samples from deeper in the soil profile will require more effort to avoid damaging the layer to be measured during excavation. Clod size distributions can also be used to calculate packing coefficients of the material, which should have added value for assessing seedbed quality of nursery soils.

Excavation of furrows is a simple field procedure, and is useful for demonstrating the effectiveness of rippers where the critical depth of tillage is closer to the suface (Figure 3). In this situation, only a small volume of soil may be effectively loosened (Andrus and Froehlich 1983); rippers operating below this depth will compact the soil around the shank (Raper 2005). Excavation assessment of tilled soil requires that the elevation of the original surface be established prior to tillage. Deep tillage will exponentially increase the amount of work required to expose the tillage boundary but excavation also provides information on how well the soil is fracturing.

Measuring the gain in soil elevation to evaluate a tillage treatment is the fastest, least destructive method of measuring tillage effectiveness. Forty pre-tillage and another 40 post-tillage measurements can be taken in as little as three hours and the average gain in elevation can be calculated in the field. A good quality laser level should be used. Establishment of a stable, untilled reference point is critical part of the method, and becomes more so if remeasured over a period of several months or years.

The gain in soil elevation provides an average value of the increase in soil porosity produced by tillage. In practice, the surface soil may be loosened more that soil deeper in the profile. Disks generally produce much larger gains in soil elevation than rippers; disks have been observed to double soil volume. Hence, a gain in soil elevation might average 20 cm, but the depth of soil penetration would only be 10cm, and the looser soil will consolidate more over time.

CONCLUSIONS

The ground-engaging implements of forestry equipment and their modifications have infrequently been evaluated for their effectiveness to till soil because of the cost and suitability for use in tilled soil. However, there are practices that allow the assessment of soil tillage to be done in the field. Measuring the gain in soil elevation is a new method for measuring tillage across larger areas and more complex terrain. The method also confirms that large increases in soil elevation are required (Figure 3) if deeper tillage of soil is to be effective, and that natural consolidation will reduce the gain in soil elevation by more than half. Nevertheless, effective deep tillage has successfully added several centimeters of increased soil porosity and/or water retention to a soil profile that is likely sustainable for several decades in the absence of trafficking.

The practical implications are two. Effective tillage produces large gains in soil elevation. Depth of tillage should not be measure from the surface of the surface of tilled soil but from the original soil surface; otherwise, the estimate of tillage depth is over estimated. These two points should help operations staff better choose and assess the effectiveness of tillage operations in the field when data are not collected.

ACKNOWLEDGEMENTS

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A TWO-STAGE GIS-BASED SUITABILITY MODEL FOR SITING BIOMASS-TO-BIOFUEL PLANTS AND ITS APPLICATION IN WEST VIRGINIA

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ABSTRACT

A two-stage approach was presented to select woody biomass-based biofuel plants using GIS spatial analysis and the multi-criteria analysis ranking algorithm of compromise programming. Site suitability was evaluated to minimize the direct cost for investors and the potential negative environmental impacts. The first step was to create a site suitability index using a linear fuzzy logic prediction model. The model involved 15 variables in three factor groups: (1) general physical conditions, (2) costs, and (3) environmental factors. The weights of the cost factors were determined using pairwise comparisons in the Analytical Hierarchy Process (AHP). The value of site suitability was reclassified into three categories (non-suitable, low-suitable, and high-suitable) using different classification methods. With a feasible plant location defined as an industrial site within the most suitable area, the second stage of the analysis used compromise programming to compare the potential sites. The criteria used to rank the potential sites included fuzzy distance to woody biomass, highways, railways, commercial airports, communities, and available parcel size. The AHP was used to compute the relative importance of each criterion. The top 10 suitable sites were determined and sensitivity analyses conducted to derive the most preferred sites. The approach was successful in taking a large amount of non-commensurate spatial data and integrating a site-based ranking algorithm to find the top locations for biomass plants. It also has great potential and applicability to other suitability and site selection studies.

Keywords: Multi-criteria analysis (MCA), geographical information system (GIS), compromise programming, biofuel, site selection

INTRODUCTION

As one of the larger unexploited sources of cellulosic biomass, woody biomass is identified as a potentially important feedstock for biofuels (Perlack et al. 2005). Site selection for a woody biomass-based ethanol plant is one of the major steps in the plant design process. The process itself can have significant impacts on the viability and profitability of the facility. Woody biomass-based ethanol plants could benefit from being near raw materials and highways/railways to keep transportation costs lower (Hamelinck et al. 2003). Locating the ethanol plant near existing industrial or power generating facilities is an efficient method to lower energy expenses. Favorable sites will also have sufficient water supply and sewer treatment. The site size should be large enough for truck traffic when moving feedstock and performing product storage. Finally, a properly located plant should also minimize environmental impacts and reduce potential problems (dust, noise, light pollution, etc.) for the community and residents who live in proximity to the plant (USDA 2006).

Several conflicting and contradicting interests exist between economic, environmental, and social criteria that are part of the decision-making process of site selection. Multi-criteria decision analysis (MCDA) can be used to evaluate these interests among different stakeholders. The most common procedure for multi-criteria evaluation is Weighted Linear Combination (WLC). The determination of criterion weights is a very important part of this method. The pairwise comparison technique, developed by Saaty in the 1970s and 1980s in the context of Analytical Hierarchy Process (AHP), is a preferred method to calculate criteria weights due to its stronger theoretical foundations as compared to point allocation and rank ordering methods (Malczewski 1999).

With advancements in technology, spatial models have become tools to aid in land suitability assessment (Vatalis and Manoliadis 2002, Vahidnia et al. 2009). Geographic Information Systems (GIS) are a very efficient and effective tool in handling a large amount of spatial data and provides capabilities for modeling, optimization, and simulation. The combination of GIS and MCDA has been proved to be an efficient way of assessing land suitability (Joerin and Musy. 2001, Gomes and Lins 2002). The weighted linear combination (WLC) is usually applied in the spatial modeling processes. The advantage of the classical WLC is that it is very straightforward. However, it is usually quantitative, and crisp input values are usually used in the modeling process, which do not reflect the real life problems exactly. To eliminate the explicit shortcoming of this method, Zadeh (1965) introduced the concepts of fuzzy sets to model the vagueness or uncertainty in the real world. Fuzzy logic and membership functions can be created to provide a way of obtaining conclusions from vague, ambiguous or imprecise information (Clementini et al. 1997). Then, the fuzzilized values, instead of crisp inputs, can be used in the spatial modeling process to derive more practical results.

The goal of this paper was to integrate components of a two-stage spatial multi-criteria analysis using GIS/spatial analysis, AHP, and a CP model to perform site selections of woody biomass-based ethanol plants. The approach was applied as a case study in the central Appalachia hardwood region of West Virginia, USA. The result will be beneficial to further analysis of the economic feasibility of woody biomass-based ethanol plants in the region.

METHODOLOGY

First stage modeling – Site suitability analysis

A site suitability index was computed for the study area using a linear fuzzy logic prediction model (Eq. 1). Variables in the prediction model are standardized and transformed using fuzzy logic membership functions so that a positive change in the value of a criterion is always associated with a positive change in the suitability or desirability of an outcome.

$$SSI = \sum \left(f_m w_m \right) * \prod b_n \qquad (1)$$

Where SSI is the site suitability index, f_m is the fuzzy value of criteria m, w_m is the weight of criteria m, b_n is the criteria score of constraint n (boolean value), and $\prod$ is the product.

In this study, 15 variables were grouped into three factors based on their relationships with the assessment of land suitability, namely (1) general physical conditions, (2) costs, and (3) environmental factors (Table 1). The site suitability was evaluated to minimize the direct cost for investors and the potential negative environmental impacts. The variables in group 2 were considered as evaluation criteria. Fuzzy logic membership functions were constructed for these variables which were expressed as distance metrics and then normalized based on the site preference. Variables in groups 1 and 3 were considered constraints. Boolean values were assigned to the variables in groups 1 and 3 based on the site preference or acceptable range, where 1 means suitable and 0 non-suitable.

Table 1: Site suitability criteria for woody biomass-based ethanol plants.

Factors	Attributes	Acceptable range	References
General physical conditions	Topography	Flat to slightly rolling topography. Slope gradient: 0-10 percent	Stans et al. (1969)
	Elevation	100-700 m above sea level	Hendrix and Duckley (1992)
	Aspect (orientation)	Southern, eastern, or western aspects	
	Land cover/land use	Shrub land, pasture, grassland, row crops	Ready and Guignet (2010)
Costs	Distance from woody biomass sources	0-80,000 m	Bain et al. (2003)
	Distance from highways	10-3,200 m	Apawootichai (2001), Koikai (2008)
	Distance from railways	10-5,000 m	Koikai (2008)
	Distance from power lines	10-1,600 m	Koikai (2008), FPL (2009)
	Distance from water bodies	50-5,000 m	Apawootichai (2001), Koikai (2008)
	Distance from sewer treatment plants	0-1,600 m	Pueblo County Board (2010)
	Distance from communities	800-5,000 m	Apawootichai (2001)
Envi. impacts	Wildlife habitat/endangered species areas	Avoid land with more wildlife biodiversity or presence of endangered or threatened species habitat	Deloitte and Touche (2001)
	Flood plain	Avoid flood-prone area	Lee and Pitchford (1999)
	Wetland area	Outside wetland area	Deloitte and Touche (2001)
	Public land	Outside public land	Deloitte and Touche (2001)

The weights of the evaluation criteria were determined using the AHP approach. In AHP, Saaty (1980) suggested a scale of one to nine for making subjective pairwise comparisons with 1 equal importance and 9 extreme importance. A consistency test was performed to assure that choices are not randomly entered. The pairwise comparisons are consistent if the consistency ratio (CR) is less than 0.1, otherwise the pairwise comparisons have to be redone until the consistency condition is accomplished (Saaty 1980).

The site suitability index was reclassified into three categories (non-suitable, low-suitable, and high-suitable) using different methods of classification (Equal Interval, Quantile, and Natural Breaks (Jenks)) in order to get more robust results. Since the availability of utilities and access to pre-existing infrastructure are the necessary conditions for the startup and operation of the plants, the alternative feasible woody biomass-based ethanol plants were selected from industrial sites within the highest suitable area.

Second stage modeling - Comparing the alternative sites using CP

At the second stage, potential suitable sites were ranked using the compromise programming method. A new set of evaluation criteria which incorporates both spatial and non-spatial data is extended from the first stage modeling, including fuzzy distance to highways, railways, commercial airports, communities, woody biomass, and available parcel size. The criteria weights were determined using pairwise comparisons in AHP.

An ideal solution for the compromise programming algorithm, as defined by Tecle and Yitayew (1990), is the vector of objective functions' values, $f^* = (f_1^*, f_2^*, \cdots, f_I^*)$. Where, the individual maximum values for criterion i, f_i^*, and minimum or worst value for criterion i, f_i^{**}, are defined using

$$f_i^* = \text{Max}\ (f_{ij}), i = 1, 2, \ldots, I \text{ and } j = 1, 2, \ldots, J, \tag{2}$$

$$f_i^{**} = \text{Min}\ (f_{ij}), i = 1, 2, \ldots, I \text{ and } j = 1, 2, \ldots, J, \tag{3}$$

The L_p metric as a compromise solution with respect to p can be expressed as:

$$\text{Min} \left\{ L_p(A_j) - \left[\sum_{i=1}^{N} (W_i) \left[\frac{(f_i^* - f_{ij})}{(f_i^* - f_i^{**})} \right]^p \right]^{1/p} \right\}, \tag{4}$$

Where $L_p(A_j)$ is the distance metric, a function of the decision alternative A_j and the parameter p (Tecle and Yitayew 1990). W_i is the standardized form of the criterion weight, which represents the decision maker's relative preference among the criteria while f_i^* and f_i^{**} represent the best and worst value for criteria *i*. The parameter p reflects the importance of the maximal deviation from the ideal point (Tecle and Yitayew 1990, Duckstein and Opricovic 1980) and it can be assigned value from zero to infinity. For p =1 all deviations are weighted equally and $L_p(A_j)$ is called Manhattan metric. In the case of p =2 each deviation is weighted in proportion to its magnitude and $L_p(A_j)$ is called the Euclidean metric. In case of $p = \infty$ the result is a min-max-problem, in which the compromise solution minimizes the maximum difference between the ideal point and the solution with respect to all indicators. In this case, Equation (4) is transformed to

$$\text{Min}\ \left\{ L_p\left(A_j\right) - \left[Max\ \left(W_i\right) \left[\frac{\left(f_i^* - f_{ij}\right)}{\left(f_i^* - f_i^{**}\right)} \right] \right] \right\} \tag{5}$$

The Eq. (4) will be run for parameter values of $p = 1$ and 2. The alternative with the lowest L_p value was the best compromise solution because it was the nearest solution with respect to the ideal point.

DATA MANIPULATION

Study site description

The study was applied in the state of West Virginia (Figure 1). The harvesting process in the state yields approximately 2.41 million dry tons of wood residues annually (Wang et al. 2006). The abundant woody biomass in the state could support several medium-sized (25-50 million gallons/year) ethanol fuel plants, given the conversion rate of 68 gallons per dry ton of woody biomass. These plants could provide a source of tax revenue to meet the ever increasing demands for energy, and help create more job opportunities for the local community in West Virginia.

Data manipulation and analysis

The spatial and categorical data used was collected from the West Virginia Division of Forestry (WVDOF 2006), Appalachian Hardwood Center (Bragonje et al. 2006), the West Virginia Development Office (WVDO 2008), and the West Virginia GIS Technical Center (WVGISTC 2010). The counties with woody biomass inventory greater than 30,000 tons per year were selected as raw material supply sources, which can support several medium-sized woody biomass-based ethanol facilities. As indicated in the Methodology section, three factor groups which involve 15 variables were considered, namely (1) general physical conditions, (2) costs, and (3) environmental factors.

To create distances associated with each of the variable in the cost group, fuzzy logic membership functions were constructed based on the site preference (Table 1). GIS spatial analyst was used to calculate distance "away from" each of the spatial features in group 2 (woody biomass locations, highways, railways, power lines, water bodies, sewer plants, and communities) in meters. Then, the *con* function which allows for "if than" scenarios was used to create the fuzzy membership functions. For example, the function of fuzzy distance to woody biomass sources would be:

Con([d_woodybiomass] > 80000, 0, (80000 - [d_woodybiomass]) / 80000)

where *d_woodybiomass* is the distance away from woody biomass sources, and 80,000 is the maximum distance in meters that would be economically feasible for woody biomass delivery.

Boolean values were assigned to the general physical conditions and environmental factors. Topograpy (slope) and aspect were derived from the elevation dataset using GIS surface analysis and reclassified into suitable and non-suitable based on the site preferences in Table 1. The resulted slope data was mapped in Figure 2a. Landcover that are suitable for plant construction include grassland/shrub and row crop agriculture. Reclassification of the landcover data is needed to create two classes: suitable and non-suitable. The spatial features (wildlife area, public land, flood plain, and wetland area) are in the shapefile format, which were converted to raster grid with 1 indicating suitable area and 0 non-suitable. The raster data of public land is shown in Figure 2b.

Figure 1: Study area.

Weight preference

A pairwise comparison matrix was created to reflect the preference or importance of the evaluation criteria in the suitability model (Table 2). The CR value (0.036) is lower than 0.1, and therefore the judgments are consistent. As expected, the criteria distance from woody biomass (0.360) was the most important factor, because shortening the hauling distance of woody biomass from the forest to the biomass-based ethanol plants would reduce the transportation cost greatly. A guaranteed supply of woody biomass at a competitive price within a reasonable radius of the plant is critical for the profitability and viability of the plant. The other criteria such as distance from highways (0.205), distance from power lines (0.146), and distance from water bodies (0.130) also received higher attention during the process of site suitability evaluation. The criteria distance from railways (0.041) appears to be the factor with the lowest importance. Compared to truck transportation, rail is more suitable for long haul of bulk goods (Mahmudi and Flynn 2006). However, the dispersed nature of biomass requires that it starts its transportation to a processing plant on a truck. Rail transshipment may be preferred in cases in which road congestion precludes truck delivery (Mahmudi and Flynn 2006).

Table 2: Pairwise comparison matrix and relative weights of the variables in the fuzzy logic prediction model.

Criteria	Woody biomass	Highways	Railways	Power	Water	Sewer	Community	Weight
Woody biomass	1.000 (0.393)	3.000 (0.495)	7.000 (0.304)	3.000 (0.429)	3.000 (0.333)	5.000 (0.263)	5.000 (0.306)	0.360
Highways	0.333 (0.131)	1.000 (0.165)	5.000 (0.217)	1.000 (0.143)	3.000 (0.333)	5.000 (0.263)	3.000 (0.184)	0.205
Railways	0.143 (0.056)	0.200 (0.033)	1.000 (0.043)	0.333 (0.048)	0.333 (0.037)	1.000 (0.053)	0.333 (0.020)	0.041
Power	0.333 (0.131)	1.000 (0.165)	3.000 (0.130)	1.000 (0.143)	1.000 (0.111)	3.000 (0.158)	3.000 (0.184)	0.146
Water	0.333 (0.131)	0.333 (0.055)	3.000 (0.130)	1.000 (0.143)	1.000 (0.111)	3.000 (0.158)	3.000 (0.184)	0.130
Sewer	0.200 (0.079)	0.200 (0.033)	1.000 (0.043)	0.333 (0.048)	0.333 (0.037)	1.000 (0.053)	1.000 (0.061)	0.051
Community	0.200 (0.079)	0.333 (0.055)	3.000 (0.130)	0.333 (0.048)	0.333 (0.037)	1.000 (0.053)	1.000 (0.061)	0.066

Note: () is normalized value.

RESULTS

Site suitability

The site suitability index (SSI) in the study area was computed, which ranged from 0 to 0.911703. The SSI was reclassified into three categories using three classification methods. If Natural Breaks (Jenks) classification method was used, the three categories would be: non-suitable (0-0.135331), low-suitable (0.135331-0.391747), and high-suitable (0.391747-0.911703). If the Equal Interval classification method was used, the groups would be: non-suitable (0-0.303901), low-suitable (0.303901-0.607802), and high-suitable (0.607802-0.911703). If the Quantile classification method was used, the three categories would be: non-suitable (0-0), low-suitable (0-0.331205), and high-suitable (0.331205-0.911703). The most suitable areas were found to be 0.19-1.68% of the total land area in all the scenarios. It was noticed that the quantile classification method provided more high-suitable area compared to the other two methods. As stated earlier, wood residue-based ethanol plants should be located in the most suitable area and have access to utilities (electricity, gas, water, and sewer) and pre-existing infrastructure. Currently, a total of 183 industrial sites are in West Virginia (WVGISTC 2010), of which 69 can provide all the required utilities. The potential industrial sites fell within the most suitable areas identified by the quantile method are summarized in Table 3. Altogether 20 industrial sites fell within the highest suitable areas, which were selected as potential sites of woody biomass-based ethanol facilities.

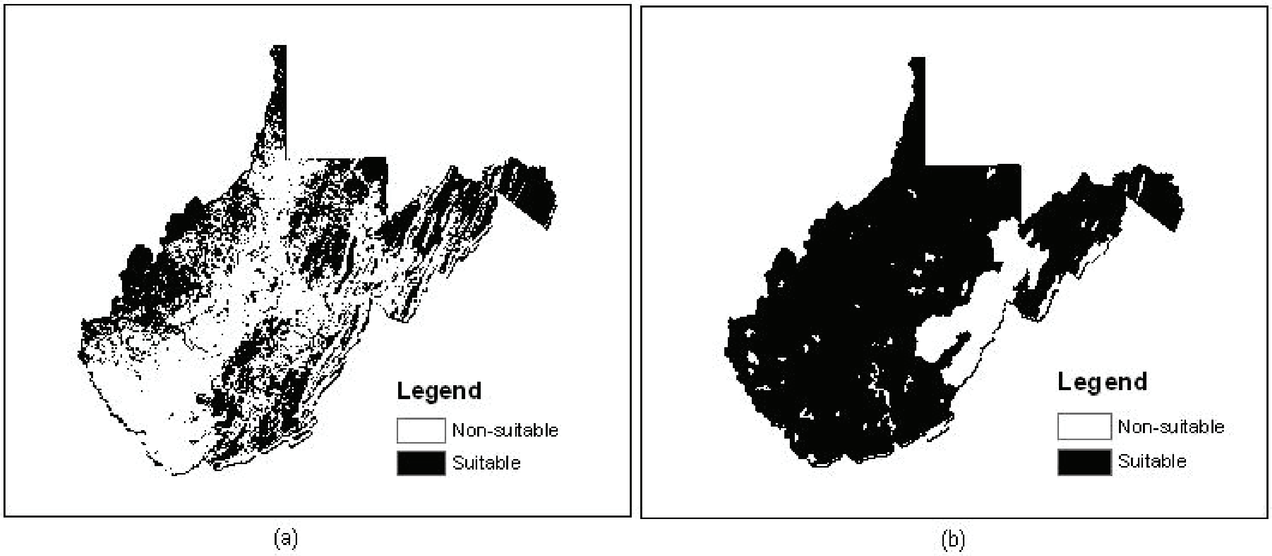

Figure 2: Example of constraints (a) slope and (b) public land.

Top ranked sites

CP was applied to compare the suitability of alternative sites derived from the first stage. The priorities of the variables in the CP model obtained from the pairwise comparison matrix were as follows: distance from highways-0.301, distance from railways-0.061, available parcel size-0.127, distance from commercial airports-0.059, distance from communities-0.083, and distance from woody biomass-0.370. The consistency ratio of the comparison was 0.054, less than 0.10, therefore the judgments were consistent and the weights can be used in the CP model.

Zonal statistics was used to compute the average distances of each alternative site to the features such as highways, railways, commercial airports, communities, and woody biomass. Zonal statistics calculates statistics on values of a raster grid within another zone dataset. Here, the zone dataset will be the potential sites, the zone field is the unique site name, and the value raster is the straight distance to highways, railways, commercial airports, communities, or woody biomass supply sources. The available parcel size of the sites was obtained from West Virginia GIS Technical Center. The values for each alternative site were normalized and the best and worst values for each evaluation criteria were determined. Next, the CP Equation (4) was run for parameter values of $p = 1$ and 2 to offer a level of sensitivity analysis as suggested by Tecle and Yitayew (1989). The best sites for each run of $p = 1$, 2 were ordered based on the L_p metric (from low to high) (Table 3). It was noted that the ranking of the alternative sites changed with respect to different p values. The final ranks of these sites were determined by summing all the ranks together and the top five ranked potential locations in WV were: Porter Farm Site (site 1, Harrison County), Saltwell Road Site (site 5) (Harrison County), Flatwoods - John Skidmore Development Site (site 2) (Braxton County), Suarez Site (site 3) (Harrison County), and Ross Site No. 1 (site 6) (Upshur County) (Figure 3).

Table 3: Industrial sites ranking.

Site No.	Rank when p=1	Rank when p=2	Sum rank	Final rank
1	1	2	3	1
2	2	5	7	3
3	3	4	7	3
4	4	6	10	6
5	5	1	6	2
6	6	3	9	5
7	7	10	17	8
8	8	7	15	7
9	9	9	18	9
10	10	8	18	9
11	11	13	24	11
12	12	15	27	13
13	13	14	27	13
14	14	11	25	12
15	15	12	27	13
16	16	19	35	17
17	17	16	33	16
18	18	17	35	17
19	19	18	37	19
20	20	20	40	20

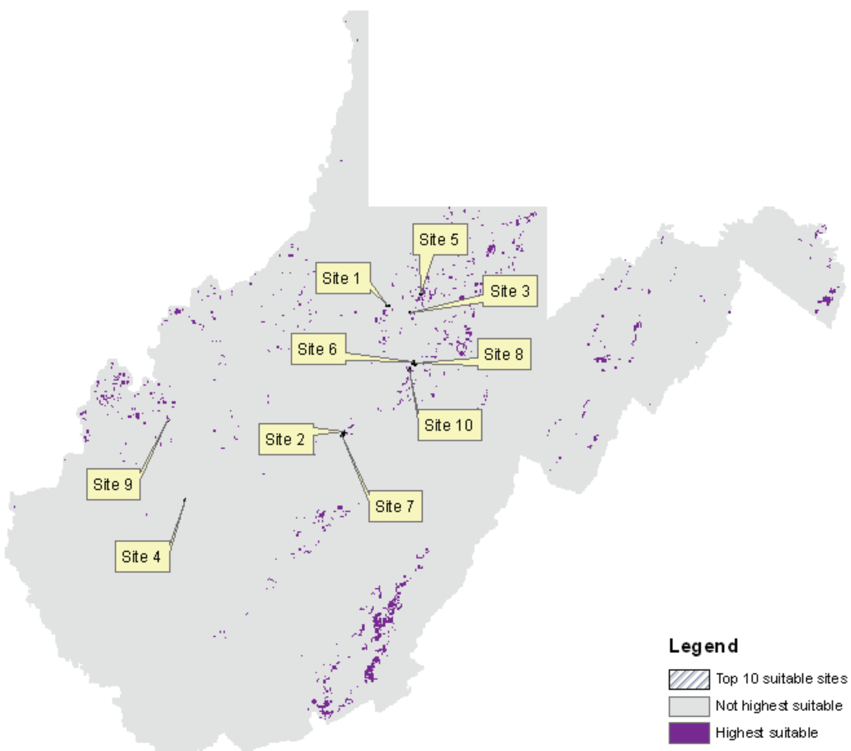

Figure 3: Top industrial site locations.

CONCLUSIONS

This study has presented a two-stage approach to selecting a woody biomass-based ethanol plant location using GIS spatial analyst and compromise programming. The land use suitability was evaluated to minimize the direct cost for investors and the potential negative environmental impacts. A fuzzy logic prediction model incorporating AHP was used to predict the site suitability index of every single cell. Industrial sites that can provide utilities and easy access to pre-existing infrastructure, and were within the most suitable area were selected as potential sites of woody biomass-based ethanol facilities. The compromise programming algorithm was then applied to rank the potential suitable sites identified from the first stage. This methodology has incorporated a large amount of economic and environmental related factors which are essential to identify the suitable sites. Decision rules for locating suitable sites for woody biomass based ethanol plants were keys to the success of the application. In fact, many other factors could be involved in the site selection process to enhance the robustness of the results, but the most important factors have been taken into consideration in the study.

The approach was applied in West Virginia, U.S. and was successful in taking a large amount of non-commensurate spatial data and integrating a regional and a local scale site-based ranking algorithm to find the top locations for biomass plants. It also has great applicability to other suitability and site selection studies.

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HIGH TONNAGE FOREST BIOMASS PRODUCTION SYSTEMS FROM SOUTHERN PINE ENERGY PLANTATIONS

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INTRODUCTION

The topic of declining fossil fuels and the absolute need for renewable energy sources is very evident in today's society. The utilization of bio-fuels is necessary to meet goals set forth in the Energy Independence and Security Act of 2007. Included in the act are standards in which bio-fuels will play a major role in ensuring national energy security and the reduction of green house gases. One of the main goals of the act is to have 36 million gallons of bio-fuel produced each year by 2022. A portion of the 36 million gallons will be derived from biomass feedstocks composed of woody biomass.

Woody biomass is available in such forms as urban residues, mill residues, short rotation woody crops, and logging residues. Currently, the availability of these types of biomass is not readily obtainable to meet the large scale quantities set forth. Eventually, short rotation crops must be utilized to conquer the United States requirements for energy. Short-rotation woody crop (SRWC) supply systems were first described in the late-1960s and early 1970s as a means of rapidly producing lignocellulosic fiber for use in the wood products industry and for energy (Tuskan 1997). These stands are harvested on 10-14 year rotation which will be attractive to landowners looking for a quick return on investment when compared to other product types from timber.

The problem lies in the harvesting, processing, and delivering of biomass to the mill in a form that is economically feasible. Harvesting systems must be balanced for the characteristics of the forest, machine types and intensity of the harvest to reflect the equipments productivity (Akay et al., 2004). Current estimated costs of this harvesting and handling system ranged from $19 to 38 U.S. per dry metric ton, less the transportation costs (Tuskan 1997). These traditional harvesting systems have not been optimized for use with SRWC and improvements in types and arrangements of equipment are still possible (Tuskan 1997). Because of the high volume and low value, a high productive operation must be set in place to mitigate the low value of the material by producing high volumes in a given time period. These systems do not need to be capital intensive and have the capability to be used for conventional round wood production due to the ever increasing fragmentation of land to private landowners who manage land differently. The system envisioned for this study is a high-speed, high-accumulation feller-buncher and a modified high capacity rubber tired skidder.

To aid in this research, TigerCat Inc., Corley Land Services, Zika Biomass Energy, and the USDA Forest service has agreed to form a consortium to develop this high productive system and evaluate its viability towards a short rotation woody biomass crop. TigerCat is one of the major producers of forest machinery in the world and have a great reputation for producing quality machines. In this research, TigerCat will implement the machine needs set forth by the consortium to engineer a feller-buncher and a skidder to loan for evaluation. Corley Land Services conducts biomass harvests currently in south Alabama. They will be the company operating the newly developed equipment because of their experience in these types of harvest. This partnership will enable a greater understanding and evaluation of the proposed harvesting operation which should show the commercial viability of the system in current markets.

Costs associated with harvesting small trees were dramatically increased due to the high capital costs associated with mechanized feller-bunchers (Frederick and Stokes, 1987). Also due to the low weight of the small trees, larger stems decrease production costs with the same machine (Akay et al., 2004). Continuous saw heads incorporated on a feller-buncher have also been shown to be highly productive. The issue with these heads is the high capital costs and high operating costs when compared to the less expensive shear heads. Shear heads have been used in conventional harvesting systems for many years but previous versions of the shear head could not meet the high productivity standards needed for short rotation woody crops. Another issue with the feller-buncher is the environmental impacts that it can place on a property. The predominant feller-buncher type is the rubber-tired drive to tree model. This model has a tendency to cause unacceptable rutting in wet weather making it extremely weather sensitive as well as a producer of erosion. Since southern pine energy plantations are generally clearcut, one must take into account that clearcutting generally produces more soil disturbance than thinning or select cutting (Reisinger and Simmons, 1988). Tracked feller-bunchers also come equipped with a boom that extends far into the stand. This enables the machine to travel in a straight path while extending its boom to the maximum length to sever trees, thus increasing productivity when compared to drive-to-tree feller-bunchers (Winsauer, 1980). Another positive effect of incorporating a shear-head in place of the continuous saw-head is the lower stump it provides. This will enable the operation to achieve increased yield of wood from the same number of stems severed. The continuous saw-head cannot achieve this result due to the deterioration of the saw-teeth when the saw-teeth meet the soil. The implementation could result in an increase of up to six inches of the largest portion of the bole of the tree being felled. Another result of the lower stump is the increased productivity of the skidder operator and the decrease in health problems associated with operating the equipment.

Ergonomics has been a major issue in the forest harvesting equipment market. The mechanization of forestry work has resulted in a sharp decline in the number of accidents in the past 20 years (Folstad, 1982). Unfortunately the mechanization has caused other long term problems for forest machinery operators due to uncomfortable positioning while operating the equipment. Despite the ergonomic and industrial hygiene improvements successively introduced, musculoskeletal complaints are currently commonplace in machinery operators. Continuous saw-heads leave stumps between 4 and 6 inches in height in which the skidder operator maneuvers around or drives over causing a very uncomfortable shake. Both of these situations lead to a loss in productivity in turn driving up harvesting costs as a whole.

The piece of equipment that is common and necessary for a conventional harvesting operation is the rubber-tire grapple skidder. This type of skidder is in current practice in most conventional harvesting systems in the southeastern United States. The skidder's purpose is to drag the felled timber to the landing where it can be loaded onto tree-length trucks or chipped and placed into chip vans. Because short rotation woody biomass will be harvested at the age range of 10-14, current versions of the grapple on the skidder will make the machinery underutilized. The reason for this underutilization is the grapple located on the skidder can only handle a certain diameter of a buddle of trees. The one factor that had the greatest impact on skidding productivity was stem size (Kluender et. al 1997). Short-rotation woody crops will be shorter than trees designated as pulp wood, but may still have the same size diameter bundle. The decrease in length of the short-rotation crops will lead to a decrease in volume and weight thus underutilizing the horsepower the skidder possesses to drag a bundle of trees. Incorporating a larger grapple to the same horsepower skidder will allow for a greater diameter bundle with the same weight as a conventional pulp wood bundle to be efficiently pulled, thus increasing biomass volume skidded to the loading deck.

In this research, we intend on meeting the following objectives:

To develop an optimal system that integrates a high productivity feller-buncher with modified skidders and a chipper to minimize production costs in harvesting short rotation woody biomass.

To develop a harvesting system that is environmentally friendly.

Design of Equipment

Feller-buncher: As stated before, TigerCat has agreed to take recommendations set forth by the members of the consortium and engineer machines that are more specialized to southern pine energy plantations. The first of which is the tracked feller-buncher. The capital cost for this modified machine will not be higher than any other tracked feller-buncher designed by TigerCat to make it attractive to perspective loggers. This machine incorporates TigerCat's state of the art ER boom system to increase fuel efficiency and strength of the boom. The design will also utilize an extremely powerful hydraulic shear to sever the biomass and a higher capacity holder on the shear for accumulation of more trees before the bundle is placed on the ground. This shear head will also incorporate a new automatic accumulating arm that will aid in operator comfort and productivity. TigerCat is making the shear thinner for speed so it will be subject to damage if trees with a butt diameter of greater than 11 inches are severed. The swing to tree boom will improve the efficiency of the machine when compared to drive-to-tree fell-bunchers currently utilized. Also by placing the feller-buncher on tracks, environmental impacts should be minimized due to the increase in surface area of tracks when compared to the more conventional rubber tires. The machine will be fitted with a data recorder for the purpose of this research to perform time studies of the productivity. Lastly, the machine will be fitted with all of the ergonomic conveniences currently available to ensure operator comfort since he/she will be moving at an extremely fast pace through a variety of terrains.

Skidder: The skidder will be the current TigerCat model 620D which is their mid-sized skidder designed for high life and low maintenance. To specialize for the larger bundles felled by the feller-buncher, the 620D will be equipped with an oversize grapple to grab a larger bundle of trees. This grapple will have a maximum opening of 143 inches compared to the conventional 138 inches. Also the machine will be equipped with data recorders for the experiment. The machine will be equipped with TurnAround^{tm}, which is a two position seating system that allows the operator's seat to rotate which eliminates his/her back twisting to see the load being skidded.

METHODS

Objective 1: To develop an optimal system that integrates a high productivity feller-buncher with modified skidders and a chipper to minimize production costs in harvesting short rotation woody biomass.

Hypothesis: The implementation of the high productive harvesting system will fell, skid, and transport >25 loads per day in an efficient manner, thus decreasing the production costs of the harvesting operation to a value that ensures the economic feasibility of a short-rotation woody crop used for energy when compared to other timber product markets.

Study Sites

To investigate these systems and meet objectives, landowners in the Greenville, Alabama will be invited to attend a meeting where they will be informed of the economic benefits of short-rotation woody biomass crops and the intentions of the study. These landowners will be surveyed to discover if they have land that would be applicable to the type of system being researched and informed that the land will be clearcut. The land desired will be have the following characteristics: planted pine plantation, minimum of 600 trees per acre, age class between 10 and 15 years, and greater than 100 acres. The study will require a minimum of two parcels for complete examination. Currently, Corley Land Services pays 6 to 12 dollars per ton for first thinning to landowners. By clearcutting these stands, the landowners will be forgoing their future sawtimber income and must be compensated more per ton for this study.

The stumpage acquired will then have a 10% cruise implemented to get an accurate account of inventory located on the property. In the cruise, we will indentify trees per acre, volume per acre, total volume, average height, and species composition. From this data, we will obtain a diameter distribution to estimate volume produced hourly by the machines. These measurements will be used to determine with the system's productivity to acquire different environmental impacts and costs associated with different stand characteristics.

Production Study

Feller-buncher

To investigate the feller-buncher engineered by TigerCat, time studies will be implemented to understand utilization, production capabilities, and flexibility with varying stand characteristics. The operator of the feller-buncher will be advised to move quickly as possible to clearcut each stand. The time studies will take place over a three week period during the summer of 2011.

The manual method will use a stopwatch to time trees cut per minute, time to harvest one bundle, and travel time between stops. The number of stems cut per minute and stems per bundle dropped will be given a volume according to the diameter distribution obtained in the cruise using Smalian's formula (Segura and Kanninen, 2005).

Fuel usage will be another variable investigated. The machines will be filled in the morning before the operation begins. The machines productive hours will be measured throughout the day along with the scheduled hours set forth by Corley Land Services. At the end of the day, the machines will be filled with a pump with a fuel meter that measures the amount of fuel inputted. Comparing the productive hours and the scheduled hours with the fuel usage will be incorporated into the economic analysis of the machine. Any down time will be recorded during the day and labeled according to the situation at hand.

Skidder

The productivity of the skidder will be evaluated using the same three methods as the feller-buncher time study. First, a stopwatch will be used to gather the time needed for the skidder to leave the loading deck and return with a bundle of felled biomass. These times will be compared to distance which will be obtained by the GPS located on the machine. Each run will be assigned a number so the time and the distance will be for the same haul. Also the data recorder on the machine will take the time of the run so it can be compared with the stopwatch to ensure its viability. Also the bundle volume will be formulated by counting the stems in the bundle and applying a volume per stem based on the stand average DBH and height

Chipper

The chipper currently owned and operated by Corley Land Services will be used to chip the material prior to transportation to the delivery mill. To get an accurate account of the material chipped, a video camera will be placed on the logging deck to record the number of loads per hour. From there, the load tickets will be acquired from Corley Land Services to obtain a volume for each particular load. From this data, volume per hour can be calculated. Also Husky Precision will loan a new chipper with higher horse power to the consortium. This chipper will be evaluated by the same process to compare productivity and cost per hour.

Economic Analysis

A complete economic analysis will be performed on both of the TigerCat machines. First, the scheduled machine hours (SMH) will be determined before the machines begin the research. Any down time for either of the machines will be identified and subtracted from the SMH to deduct productive machine hours (PMH). The down times will be classified as maintenance, breakdown, stand hindrance, weather, other machine interference, or human caused. By computing a ratio from PMH and SMH, one can determine the production efficiency and based on the qualities of the downtime, lacking features of the system can be identified.

Using the time study data gathered via stopwatch, measurements, data recorders, and video camera, the consortium will formulate a volume per hour produced by each machine as well as the entire system. Because of the varying stand characteristics, the volume will be calculated in a stratified form so conclusions can be made on the influence of stand density and maneuverability. Furthermore, costs associated with operating the equipment encompass labor, fuel, capital costs and depreciation, maintenance, and overhead will be calculated on a per ton basis. By calculating both volume and costs to obtain that volume, an accurate estimate can be developed to understand the viability of the system at current delivery prices set forth by the biorefinery.

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WHAT IS THE BEST RIGGING CONFIGURATION TO USE IN NEW ZEALAND CABLE LOGGING OPERATIONS?

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ABSTRACT

There are a number of cable logging documents which describe the various rigging configurations, but very few provide any detailed information as to what system will be more productive, or safer, under what stand and terrain conditions. The purpose of this study was to interview experienced cable loggers in New Zealand to find out what they knew about rigging configurations and their applications. Fifty people across eight different regions participated in the study including company planners, yarder operators, foreman, and crew owners. The majority of participants had a good understanding of four of the most common rigging configurations; North-bend, Running Skyline (Scab), Highlead, and Shotgun. Results show that the North-bend system was the most commonly used rigging configuration with 48% of individuals stating they used it more often than others. Less often used rigging configurations generated lots of interest and discussion, but knowledge and experience with these configurations was highly variable. Motorized carriages for example were recognized as versatile for long haul distances, broken terrain, and for obtaining full suspension over Stream Management Zones (SMZ's). However, only 4% stated they used motorized carriages most often, and only 28% said they had used them in the last five years. There is often a wide overlap in applicability of rigging configurations, but choosing one to match conditions can be difficult. Perceived advantages and disadvantages of each system are presented in the paper. This study aims to make the configuration selection process easier by sharing the knowledge and experience of industry professionals.

INTRODUCTION

Cable logging practices date back centuries in Europe, but modern cable yarding practices were developed in the late 19th century with the advent of steam powered engines like the Dolbeer Steam donkey in 1881 in Eureka, California (www.ci.eureka.ca.gov). Modern cable logging with integrated tower yarders (referred to as haulers in New Zealand) was introduced into plantation forestry in the 1950's, with the development of diesel yarders, and have continued to be the preferred method of extracting timber on slopes limiting conventional ground based equipment around the world (Kirk and Sullman 2001). Cable yarding is also preferred due to its' environmental benefits over ground based yarding, because the partial or full suspension of logs generated results in minimal soil disturbance (McMahon 1995; Visser 1998). Alternatives, such as modified ground-based equipment and helicopters exist for the extraction of timber on steep slopes. Helicopters are not often preferred due to their high rate of fuel consumption and expensive operating costs. Modified ground-based equipment are limited in their application due to their short economic yarding distance and their difficulty in traversing rough terrain.

Despite its wide use and environmental benefits cable logging is expensive, has tended to have high incidence of accidents to workers, and is generally less productive than ground-based methods of harvesting timber (Slappendel et al. 1993). Even those who have had only a brief introduction to cable logging appreciate that it is more complex than either tractor or skidder logging.

Cable yarding practices can vary widely world-wide, with significant differences in types of machines and the selection of rigging and accessories. Two main regions of significant development include the Pacific North West and central Europe. Cable logging as it is practiced in New Zealand differs in several respects from how it is practiced elsewhere, especially in terms of choice of rigging configurations. The reasons are various, but the nature of Pinus *radiata*, the value of the wood recovered, features of New Zealand's terrain and climate, and the reliance on plantation forestry, are all factors (Liley 1983).

Evanson and Amishev (2010) have investigated new equipment development options to push the limits of ground based machinery on steep terrain. However, as ground based machinery become increasingly dangerous and less productive to operate on steep terrain (> 45% slope); cable extraction of stems still remains as one of the only viable options for harvesting.

When using a yarder for cable extraction the main criteria determining the extraction method to be used is the ground slope or profile, of the area to be harvested (Visser 1998). The first decision made is whether the extraction of timber will be uphill or downhill. Then there are a variety of factors including desired lift, tower height of the yarder, number of drums for the yarder, crew size, and availability of carriages and gear, to name a few, which all determine which rigging configurations can be used. There are about ten different basic cable yarder rigging configurations and literately hundreds of variations when including different carriages and attachments. Therefore, a given stand of timber can be typically be harvested with a range of rigging configurations.

One of the most common challenges in cable logging operations is deciding when and where to use which rigging configuration and furthermore, which gear to pair with the chosen configuration. There are a number of cable logging texts describing the various rigging configurations, like the LIRO Cable Logging Handbook (Liley, 1983), Yarding and Loading by Oregon Occupational Safety and Health Division (OSHA, 1993), and Cable Logging Systems (Studier and Binkley, 1974). There are also many documents which provide detailed information about safety for workers in cable logging operations like the Approved Code of Practice for Safety and Health in Forest Operations (Department of Labour, 1999), the FITEC Best Practice Guidelines for Cable Logging (FITEC 2000), the Cable Yarding Systems Handbook (WorkSafeBC 2006) or OSHA's Oregon Bush Code (OR-OSHA 2008). However, very few provide any detailed information as to which system will be more productive, or safer, under given stand and terrain conditions. Before improvements to current practices can be made, one must first gain a better understanding of the abilities and limitations between the various cable logging systems.

The objective of this study was to determine the current use and applications of rigging configurations and equipment in New Zealand cable logging operations. Emphasis was placed on appropriate rigging configuration selection, given their perceived advantages and disadvantages, as well as some operational variables such as yarding distance and deflection.

METHODS

A questionnaire was developed and interviews were conducted in person from a variety of regions in New Zealand. The rigging configurations referred to in this report are as presented in Studier and Binkley (1974). During visits to active logging operations, forest management offices, and equipment manufacturers, interviews were conducted with the most knowledgeable and experienced person with cable yarding on site. Individuals who contributed to the study had the option to remain anonymous. Basic information collected included; job title, the company they worked for, equipment they owned, and which rigging configurations they were most familiar with. Then the advantages and disadvantages of each rigging configuration were noted. Finally some terrain scenarios were discussed in terms of which rigging configuration might be best suited. Each of the interviews asked the same questions in the same order so that the answers could be easily compared from person to person and region to region.

Interview data was then entered into Microsoft Excel 2007 spreadsheet software. Summary statics as well as graphs and tables were then generated for each of the interview questions using functions within excel.

RESULTS AND DISCUSSION

Survey Participation

A total of 50 interviews were conducted, from eight different regions in New Zealand and one region in the United States. Most (52%) were from the North Island, although Otago/Southland on the South Island was equally one of the most heavily sampled regions (20%). The majority of interviews were with crew owners who acted as foreman, followed by company planners, crew foreman, and yarder operators. Interviews were also given to equipment operators and in some cases crew owners not onsite with their logging crews.

Use and Knowledge of Rigging Configurations

When asked which rigging configuration they most often used 48% stated North-bend, while the second most common configuration was Running Skyline followed closely by shotgun carriage (Figure 1). Despite North-bend's popularity most had used various rigging configurations recently.

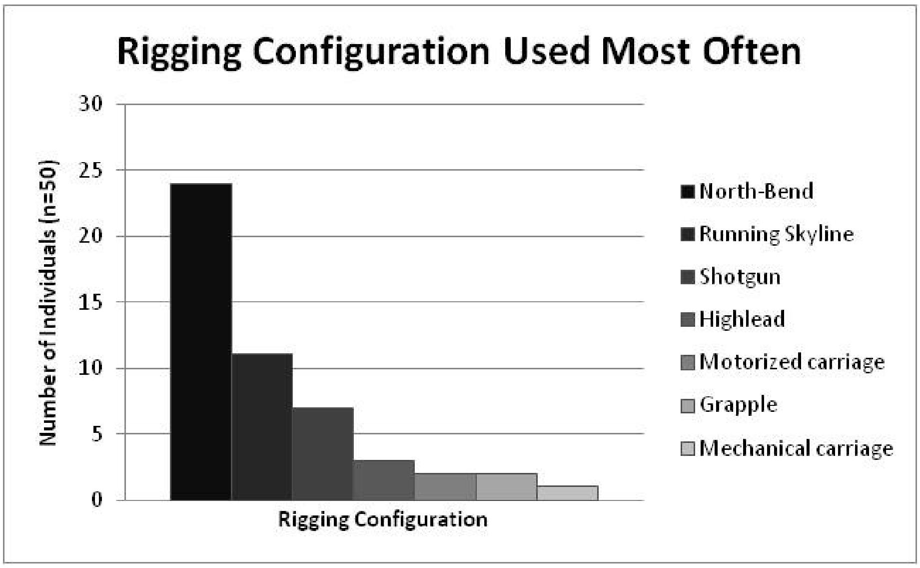

Figure1: Rigging configuration most often used by survey participants.

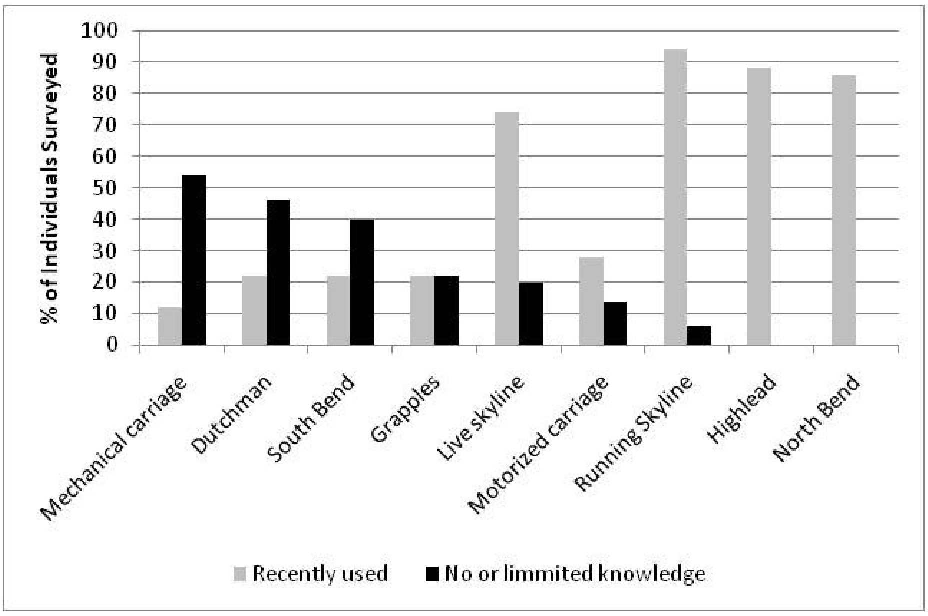

Figure 2: Study participant's recent use of various rigging configurations, as well as configurations and equipment which survey participants stated they had no or limited knowledge of.

More than 70% of survey participants said they had used Highlead, Running Skyline, North-bend, and Shotgun carriages within the last five years. However, it's interesting that 28% or less said they had used any of the other rigging configurations, including either motorized or mechanical carriages, within the last 5 years (Figure 2). Survey participants may be less likely to use alternate rigging configurations depending on terrain suitability or availability of personnel and equipment. However, the results indicate that perhaps they are deterred from using alternative rigging configurations because of their lack of knowledge or experience (Figure 2). The rigging configuration that most study participants (54%) said they had limited knowledge or experience with was mechanical carriages, which corroborates with only 12% saying they have used one in the last 5 years. Other configurations and equipment that individuals stated they had limited knowledge of were Dutchman, South-bend, and Grapples, all of which had limited use by study participants over the last 5 years.

A separate section of the interview asked participants about their experience and knowledge with swing yarders. The most recent survey indicates that about 25% of all yarders currently operating in New Zealand are swing yarders (Finnegan and Faircloth, 2002). 46% of the participants were familiar enough to discuss them in detail and only some of them owned or used one. While, 16% claimed they didn't know much about them at all or had never seen one working. This may explain why less than 25% of individuals have used a grapple in the last five years (Figure 2). Although many of the rigging configurations previously mentioned can be setup up with an integrated tower yarder or a swing yarder, some configurations like grapples are almost exclusively used in New Zealand on swing yarders. Many indicated that swing yarders were advantageous for short haul distances and their ability to work on small landings rotating and landing wood to the side out of the shoot. Concerns with swing yarders were with their relatively short tower height and complexity, as well as their high cost.

Advantages and Disadvantages of Common Rigging Configurations

Brian Tuor, a consultant and trainer currently lives in Oregon but has worked extensively in New Zealand, concluded his response with the following statement:

"In my experience, systems are often chosen not based on any or all of the criteria but on what the crew knows and are familiar with. This is not always bad, because given the wide overlaps in applicability of the systems, a crew is often more productive and safer using the system they know and are familiar with, rather than trying to learn and adapt to a new system. However this tendency keeps the crews from learning new and often more appropriate systems."

Some of the most informative and interesting results came from the discussions about the advantages and disadvantages associated with different rigging configurations and equipment. The following tables summarize these findings for the four most often used rigging configurations; Highlead, Running Skyline, North-bend, and Shotgun carriage. Responses were grouped during the analyses phase, and only those where three or more of the interviewees noted a similar advantages or disadvantage is presented.

Highlead

The most common advantages of Highleading were the simplicity in operation and setup, as well as its ability to function when there is limited to no deflection which prohibits most other configurations from being used (Table 1). Despite the advantages, Highleading's lack of lift poses a problem for the level of ground disturbance, breaking of gear and stems, and productivity (Table 2).

Table 1: Advantages associated with highleading.

Response	#
Quick to setup/Simple to operate	25
Good when there is limited deflection	19
Easy line shifts/No skyline	11
Good for short hauling distances	9
Ability to pull from blind areas	9
Productive system	8
Good last resort when nothing else works	7
Cheap system to run/Less expensive yarder	4

Table 2: Disadvantages associated with Highleading.

Response	#
No lift/Rigging drags on ground	31
Ground disturbance	17
Little control of drag/Drags get stuck/Breakage	19
Slow pulls = low productivity/Low Payloads	17
Rope wear	9
Chains tangle	7
Hard on breakerouts/Hazardous to workers	4
Fuel use is high	4
Loss of hp power due to breaking tail rope	4
Limited to short distance/terrain conditions	4

Running Skyline (Scab or Grabinski)

The second most commonly used of all configurations was Running Skyline, which many prefer because like Highleading it is simple to setup and run, but it provides more lift (Table 3). The ability to make quick line shifts especially when using a mobile tail hold, and the increased lift is thought to increase overall productivity making Running Skyline one of the popular rigging configurations. Although Running Skyline is relatively quick concerns came with the configuration's payload capacity and yarding distance, as well as functional problems with gear such as line wrapping, rope wear, and brake wear. Its improved lift over Highlead is good but, often isn't enough to minimize soil disturbance or to be suited for all terrain conditions (Table 4).

Table 3: Advantages associated with Running Skyline (Scab or Grabinski).

Response	#
Simple/Quick setup & line shifts	30
Productive/Quick	19
Simple to operate/less skill required	17
Less ground disturbance/More lift than highlead	11
Minimal deflection required/Good for short distances	7
Easy to get slack in rope/Easy to land gear	4
Gear elevated off ground/Less rope wear	3
Can downhill yard	2
Less hp required/More pulling strength	3
More control over drag	3

Table 4: Disadvantages associated with Running Skyline (Scav or Grabinski).

Response	#
Rope wear & tangle/Gear break	17
Brake wear/Pulling against self/Tail pull	10
Short distances/Terrain limited	11
Lack of lift/need good deflection/need tall tower	14
Productivity/Smaller Payloads/More hp required	10
Fuel consumption	6
Soil disturbance	5
Lots of line shifts/Line shift time without mobile tail	3

North-bend

The most commonly used rigging configurations was North-bend, primarily because of its' versatility and ability to lateral yard due to bridling. Other common advantages were its robustness because crews find it hard to break and it's easy on the yarder and ropes, while still having good productivity and payload capability (Table 5). Despite being the most popular rigging configuration there were many disadvantages stated about the configuration. Most of the disadvantages had to do with longer setup time as well as longer and more complicated line shifts. The temptation to bridle to far often resulted in lower production and higher operating costs were of concern (Table 6).

Table 5: Advantages associated with North-bend.

Response	#
Bridling capability/Lateral yarding/Versatility	25
Increased lift/Less soil disturbance	23
Productivity/Good payloads	18
Easy setup and rope shifts/Simple to operate	11
Robust/Hard to break/Easy on machine & ropes	8
Good control over drag/Getting around obstacles	8
Good for long distances	3

Table 6: Disadvantages associated with North-bend.

Response	**#**
Longer skyline shifts/Tempted to bridle too far	12
Longer setup/Cost of operation	11
Production	8
Hard to drop gear to right location for hook-up	7
Suspension/Less control over drag/Breakage	6
Walk in & out for breaker outs	5
Lack of skill	5
Rope wear	5
Overloading hazard/Pull out stumps	4
Blind leads/Deep gulley's	4
Long distance yarding	3
Landing and unhooking	3
Rider block and fall block hit together	3

Shotgun

Another one of the most commonly used configurations was live skyline with a Shotgun carriage. This configuration is very popular among users because highly regarded as the cheapest configuration to run due to its' limited fuel use. It is also very simple to operate and setup, productive, and tends to maximized deflection and payloads. It has good suspension of logs which often makes it a useful choice to fly logs over creeks or around obstacles (Table 7). Some of the disadvantages with this cheap configuration to operate are the expensive maintenance due to brake, rope, and gear wear. The configuration is also limited to terrain where you have a steep enough cord slope for gravity to outhaul the carriage. Although the concept is simple there is a hazard of overloading the skyline and therefore you need to have good communication and breaker outs need to be well trained (Table 8).

Table 7: Advantages associated with Shotgun.

Response	**#**
Maximizes deflection & payloads/Full suspension	19
Fuel use/Cheap to run	17
Productivity/Quick	16
Easy setup/Simple to operate	14
Less hp required	3
Easy on breaker outs/Easy to land logs & drop gear	3

Table 8: Disadvantages associated with Shotgun.

Response	#
Limited to terrain/Can't do back face without slack line	13
Brake, rope, & gear wear	7
Complicated/Harder line shifts	6
Overloading hazard/Need good communication	6
Deflection/Soil disturbance	6
Productivity	4
Hard to get caught drags unstuck	4

Variables for selecting the appropriate rigging configuration

Yarding distance

Through the interview process we noticed that one commonly used factor for determining the appropriate rigging configuration is haul distance. Some rigging configurations like highlead are better suited for short distances while others are better suited for long haul distances. However, defining what is a short and what is a long haul distance proved to be a challenge. Most participants in the study would agree that somewhere around 300 meters or less is a short haul distance (Figure 3). When it came to determining what a long haul distance, responses varied even more. Most stated that more than 300 meters was long, but many would state that a long haul distance is greater than 400 meters and some would even say 500 (Figure 3). The results suggest that maybe we don’t understand these configurations at the 100 meter level of resolution or maybe there are more factors that come into play.

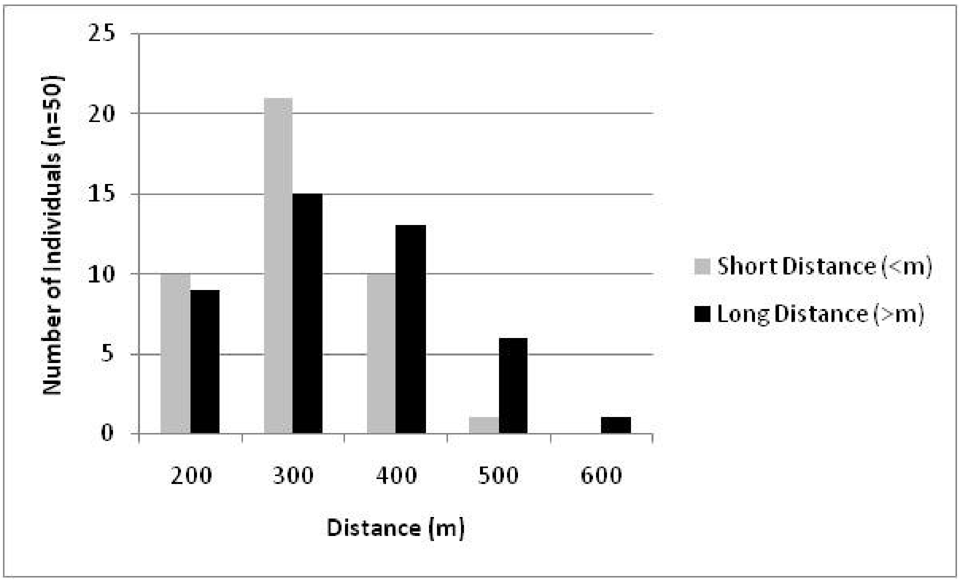

Figure 3: What survey participants perceive as a short and as a long cable logging haul distance in meters.

When asked which rigging configurations were preferred for short and long hauling distances the answers again varied. Most individuals (32) would agree that Running Skyline would be a good option for short distances. Other than Running Skyline there were a variety of configurations that participants stated would work well for short haul distances including, shotgun, highlead, grappling, and even North-bend (Table 9). Statements on the preferred configuration for long haul distances were heavily concentrated to 3 different configurations. Half or more of individuals interviewed would agree that North-bend or shotgun are probably best suited for long distances followed closely by motorized carriages (Table 9). The choice of motorized carriage is interesting to note since only a few individuals stated they used them most often, and less than 30% say they have used one within the last 5 years.

Table 9: Participants preference in rigging configurations for short and long haul distances.

Rigging System	Short (#)	Long (#)
Running Skyline	32	9
Shotgun	19	25
Highlead	15	1
Grapple	13	2
North-Bend	12	29
Motorized carriage	7	15
Slackline	2	7
Mechanical carriage	1	2

Yarding direction

Yarding direction is another main criterion for determining which rigging configuration to choose, since some configurations are not mechanically capable or are inherently dangerous to operate when pulling downhill. When participants were asked which configurations they preferred for pulling uphill the results were similar to which systems they use most often (North-bend, Shotgun, Running Skyline) this is most likely because most of the time they are yarding uphill. However, again note the preference to use a motorized carriage which are not commonly used yet 15 individuals said would work well (Table 10). For downhill yarding the preferences were concentrated to mainly two different configurations, Running Skyline and North-bend (Table 10). Most individuals said Running Skyline would work well and was preferred due to its simplicity, but many would also prefer North-bend for a little more control of the drag. Highlead and grappling were also common answers, highleading is not ideal due to associated ground disturbance, and grapples usually require the use of a swing yarder which many individuals do not possess.

Table 10: Participants preference in rigging configurations for uphill and downhill yarding.

Rigging System	Uphill (#)	Downhill (#)
Shotgun	34	0
North-Bend	19	20
Motorized carriage	15	2
Running skyline	7	32
Grapple	4	9
Highlead	3	10
Mechanical carriage	2	0
South-Bend	2	1
Slackline	2	6

Deflection

Deflection is probably one of the leading criteria for appropriate rigging configuration selection, since it ultimately dictates ground clearance and payload capacity. Often deflection is expressed as a percentage of the span length with low deflection being less than 6%, and high deflection being greater than 15%. When asked which rigging configuration was preferred given deflection alone the top four responses consisted of only six different rigging configurations (Figure 4).

Highleading was most popular for low deflection scenarios since it often works well with little deflection where others do not, and coincidentally it is not even considered when deflection is high or extreme. Running Skyline was the second highest choice for both low and medium deflection scenarios but then becomes less popular as deflection increases. North-bend was a popular choice and results show how versatile the configuration is since it was preferred in almost any deflection scenario. Although north-bend may be difficult to operate in low deflection settings, it is still most preferred configuration in medium, high, and sometimes extreme deflection settings. The shotgun configuration is another that works given most types of deflection. Shotgun never seems to be the first choice but higher consideration is given to the configuration as deflection increases. Grapples are considered to be preferable in any scenarios other than low deflection, but are less popular than other most likely due to other variables, but also because many crews do not own swing yarders which they are commonly used with and the limited experience and knowledge surrounding them. Most interesting to note was the preference for motorized carriages, which were selected for all deflection scenarios except for low, but again are not as widely used as other configurations. Motorized carriages appear to have a growing preference as deflection increases, and are the most preferred in extreme or very high deflection scenarios.

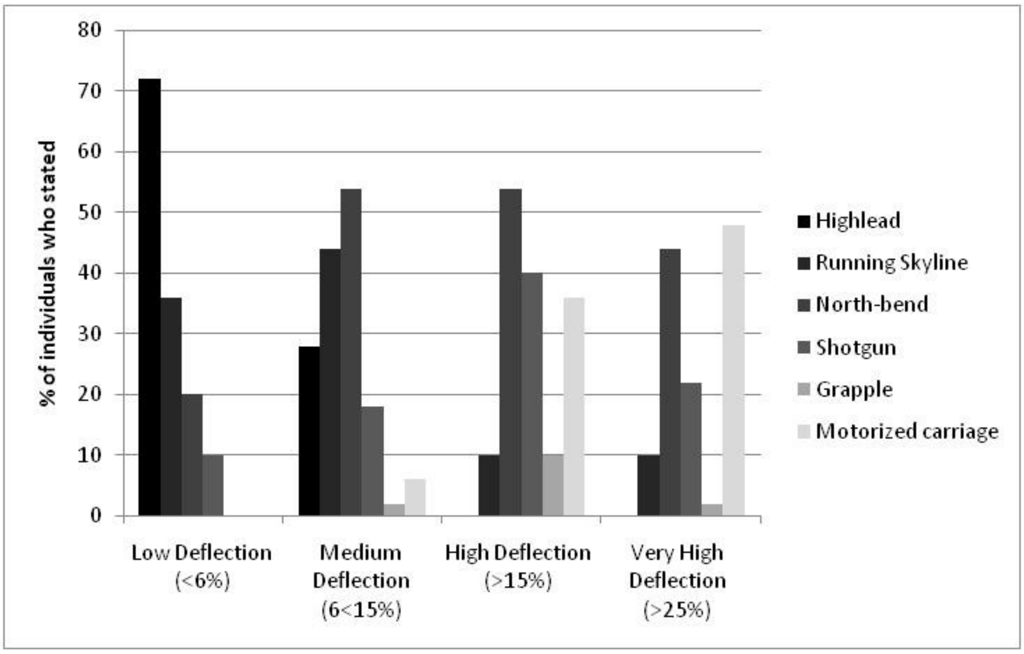

Figure 4: Participants preference in rigging configuration given percent deflection.

Operational constraints scenarios

Part of the interview process asked individuals which rigging configurations had the ability to handle certain operational constraints or challenges. Excluding all other variables participants then stated which configurations they thought would work best given the scenario.

Pulling across broken terrain or incised gulleys

Inconsistent terrain is a common challenge face in New Zealand cable logging operations. Sometimes crews have to pull across several incised gulleys or small ridges. This often times requires the load to be raised and lowered during inhaul to navigate potential obstacles. Most participants stated that North-bend was their preferred rigging configuration for this scenario, but motorized carriages were also given strong consideration (Table 11).

Having to pull away from or around a native bush boundary or other obstacle

Native tree species are not allowed to be harvested in New Zealand so any native patches of trees have to be protected and all operations are required to work around them. Pulling away from or around obstacles like native bush boundaries or rock faces often requires the configuration to have a lateral yarding capability. Again North-bend was the preferred choice for most participants due to its bridling capability. Motorized carriages were also highly regarded due to the slack pulling capabilities which allows them to lateral yard (Table 11).

Ability to fly trees over a watercourse or stream management zone (SMZ)

Best management practice guidelines in New Zealand prohibit trees from being yarded through or drug across any major watercourse. The only acceptable way to yard across a watercourse is obtained through full suspension of the load, so there is no ground disturbance. Success if often determined by the ability to hold the load fully suspended during inhaul. Motorized carriages were the most common choice most likely due to their ability to lock the load in place at a given height while yarding across a watercourse (Table 11). North-bend and South-bend were also popular choices due to their vertical lifting abilities. However, the bend systems pose a slight challenge where the load can be unexpectedly lowered during inhaul if there is insufficient tension in the tail rope (haul back).

Table 11: Participants preferred rigging configuration for yarding across broken terrain.

Rigging Configuration	Across Broken Terrain (#)	Around Native Bush (#)	Over SMZ (#)
North-Bend	27	33	15
Motorized carriage	16	21	33
South-Bend	6	8	14
Slackline	5	3	9
Highlead	4	2	0
Shotgun	3	2	2
Running Skyline	2	1	3
Grapple	1	0	1
Mechanical carriage	1	1	0
Block in the Bight	0	3	0

CONCLUSION

This study discussed the responses and opinions of 50 individuals practicing cable yarding in New Zealand at a professional level. The majority of these individuals were crew owners acting as foreman, followed by company planners and crew forman. The most widely used rigging configuration was North-bend followed by Running Skyline (scab), shotgun, and highlead. Less than 30% of participants use other configurations outside of these four in the last five years. More than half of individuals interviewed stated they had no or limited knowledge with mechanical carriages, and 40% or more said they also had no or limited knowledge with Dutchman and South-bend.

Although there appears to be dependence on a few common configurations, most participants were interested in, or recognized the potentials of, other configurations. In particular, motorized carriages which were not widely used, but recognized as having great versatility with their ability to work in higher deflection settings, pull across broken terrain, around obstacles, and across water courses. Swing yarders were also of great interest, yet only 46% of individuals could discuss them in detail. They are also recognized as being versatile and can work on small landing and are commonly paired with grapples. Coupling a swing yarder with a grapple was also of great interest, but 20% say they have no or limited knowledge with grapples and only 20% say they have used one in the last five years.

It's clear from the results we have collected that some configurations are more often used than others, and that there are certain advantages and disadvantages associated with each. There are also criteria like yarding distance, direction, and percent deflection which help steer ones decision for selecting the appropriate rigging configuration. However, there is no clear indication as to which rigging configuration is best. This is most likely due to the versatility of certain configurations and the wide overlap of application between systems. In order to guide practitioners towards which system is most applicable given their harvest setting, future research will compare and analyze configurations based on a combination of some of the variables and criteria mentioned in this study.

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IN-WOOD SCREENING OF WOOD GRINDINGS FOR BIOMASS FEEDSTOCK APPLICATIONS

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ABSTRACT

Logging residues in the US South are often piled during harvests of roundwood or clean chips and later processed by horizontal grinders to create woody biomass fuels. Recently some purchasers of fuelwood have restricted or stopped their purchase of ground residues due to concerns about contaminants such as soil and sand that increase the ash content and lead to fouling of boilers. To reduce these issues with ground logging residues while ensuring available markets, some contractors have started screening grindings by processing them through trommel screens to reduce the contamination and ash content. We are currently studying the impact of the type of residue processed (roundwood residue from final harvest clearcuts vs. clean chip residue from first thinnings), grinder size (460 hp vs. 780 hp), and drying time in the field prior to recovery (4 weeks vs. 8 weeks).

INTRODUCTION

Currently, a mere 8% of US total energy consumption is produced from “renewable” sources (EIA 2010). These sources include solar, geothermal, wind, biomass, and hydro. Of these sources, only biomass has the potential to provide liquid fuels that can be used to help power the current fleet of transportation vehicles and reduce the nation’s reliance on imported petroleum. Higher market prices for fossil fuels as well as proposed policy changes to support renewable energy and/or reduce fossil carbon emissions have recently led to a large number of bioenergy projects being announced which will consume woody biomass. Projects announced for North America as of March 2011 could potentially consume nearly 70 million green tons (64 million tonnes) of wood biomass feedstock if all were built as proposed (RISI 2011).

The U.S. South region is particularly well equipped to provide woody biomass for energy applications (Munsell and Fox 2010). Work has already been done to develop co-firing systems that are operationally proven and have a number of environmental and economic benefits (Demirbas 2003). With the potential for woody biomass use in renewable energy processes, some work has gone into developing methods for harvesting and collecting this material.

Numerous studies have examined the use of logging residue as a primary source of biomass fuel in energy and biofuel production (Takuyuki Yoshioka et al. 2006, Galik, Abt et al. 2009). In many cases logging residue is currently not utilized as a part of normal forest harvesting techniques. However, a recent survey of top state forestry officials in the United States identified high harvesting and transportation costs for woody biomass from forests as the top constraint to expanding this potential new industry (Aguilar and Garrett 2009).

There is a demonstrated need to "pretreat" residue before transport to an energy facility (Takuyuki Yoshioka et al. 2006). Objectives of pretreatment typically include resizing the material to facilitate improved transportation to a facility, storage at a facility, and eventual processing for energy applications (Yancey et al. 2010). Numerous in-woods options have been developed and tested, with the majority of study focusing on chippers and vertical (tub) or horizontal grinders (Asikainen 1998). Horizontal grinders appear to be especially useful in this setting, since they allow for a varied and versatile feedstock (Arthur, Kepner et al. 1982).

However, there is only a small body of literature examining the use of horizontal grinders in energy applications.

There are other issues related to using logging residues for energy that must also be addressed. There are well-documented concerns with fouling and slag formations within the boilers of biomass fired energy facilities due to aluminosilicate contaminants such as sand and soil (Miles, Baxter et al. 1996, Ohman, Bostrom et al. 2004, Niu, Tan et al. 2010). This issue is of increased concern with logging residue, as it is frequently piled for extended periods of time, increasing contamination. The fouling reduces the efficiency of the boiler and forces the need for more frequent downtime to allow maintenance to remove the slag. This is less of a problem with some boiler technology (e.g., bubbling or fluidized bed) than others (e.g., stoker-grate). But even with technology that is not as sensitive to sand or ash in the system, it creates an additional byproduct that must be disposed at additional cost. For example, for each 100,000 tons of wood that an electric plant that uses per year of wood at 50% moisture content, one percent of ash content in the feedstock represents 500 tons of ash requiring disposal or nearly 1.5 tons per day. Electric plants are typically on a scale that uses 5-10 times this amount of wood, thus magnifying the size of the disposal issue. In addition, it is not uncommon for some residues to have 5-15% ash content as recovered from the forest, again further compounding the ash related issues.

Another significant and growing market for woody biomass in the US South is for wood pellet plants that produce either "white" pellets for use largely in residual heating applications or "brown" pellets that are primarily shipped to UK and EU markets for co-firing with coal for electricity production. These pellet products have ash content tolerances that are often 0.5% for white pellets and 1.0% or less for brown pellets. In either case, sand or other silica contamination significantly increases the wear on the dies used to form the pellets, shortening their life and increasing plant costs and downtime. For these reasons, pellet manufacturers typically pay a premium for clean feedstocks and recently have focused on roundwood sources of forest fiber rather than use of logging residues. This leads them to directly compete with established pulp and oriented strand board markets for higher priced, but cleaner, roundwood material.

Consequently, direct combustion of some forms of biomass may be limited (Balat and Ayar 2005). Proposed solutions include the use of additives such as kaolin and limestone to reduce the size of ash deposits (Ohman, Bostrom et al. 2004).

Perhaps a better approach would be to reduce the amount of fine material contaminants at the source, before the fuel is transported to an energy producing facility. There are a number of sifting or screening processes that can be used to separate the desired wood fuel from any fine material. Specifically, trommel screens can be used between a grinder and a hauling truck in this capacity. *Trommel screens* are screened cylinders used to separate materials by size. Some biomass harvesting contractors in the southeastern United States have recently added trommel screens to their horizontal grinding operations to reduce the dirt and ash content of the material produced (Figure 1). These typically have screen openings of 10-15 cm (~0.5 in) and reduce the amount of fines and dirt in the material screened. The use of screens was prompted by woody biomass users (typically pulp mills) that experienced boiler issues with unscreened grindings and ceased purchasing these feedstocks. While this approach is used by a few contractors that supply biomass users in a few locales, to date this solution has not been well tested and reported in the literature.

Figure 1: A trommel screen receiving grindings from a horizontal grinder in a planted pine stand in South Carolina, January 2011.

We are currently studying these grinder systems using screens to quantify their effectiveness at reducing ash content of fuels with two common forms of residual forestry materials – roundwood residues and clean chipping residues (Figure 2). The field work on this project is now half completed, so this paper serves as a status report of the project and discusses the results expected in the near future (by late 2011).

Figure 2: A residue pile resulting from a roundwood logging operation (top) and a pile from a delimbed, clean-chipped thinning (bottom).

OBJECTIVES

Our goal is to determine the potential benefit of reducing the ash content of material fed through horizontal grinders in the woods. We are assessing the potential costs and benefits of this modification to grinding operations by examining contractors' production rates and feedstock characteristics with a screen in place. Grinding operations following both (1) clean chipping operations utilizing chain flail delimbers, and (2) roundwood operations using pull-through delimbers will be measured separately to determine if feedstock characteristics differ based on the type of harvesting system used.

We are examining systems using trommel screens with the following objectives in mind:

1. To assess the effectiveness of trommel screen operations in reducing ash content with forest residues that have been drying for up to 8 weeks,

2. To compare differences between screened grindings produced from residues left by roundwood and clean chipping operations, and

3. To understand the production and cost issues associated with operating grinder/trommel screen fuelwood systems.

METHODS

We are conducting this study by monitoring and collecting samples from an active fuelwood removal operation where a logger is utilizing a trommel screen to remove fine materials from the grinding stream using piled logging residue (tops, limbs, etc.). Our industry partner on this project is Collum's Lumber Products in Allendale, South Carolina. They have harvesting crews that produce clean chips in-woods with flail delimbing as well as conventional roundwood operations. Fuelwood is typically collected behind clean chip operations using horizontal grinders and trommel screens but not after roundwood operations. However, they graciously agreed to include some roundwood harvests to assist with our study design.

We are evaluating grinding and screening on pine plantation sites that received roundwood or clean chip harvests either 4 weeks or 8 weeks prior to the fuel harvesting (Table 1). Roundwood harvests in this area are typically clearcut final harvests while most first thinnings are performed with clean chipping crews. They deploy two sizes of grinders – a Peterson 4700B (780 hp) and a Peterson 2400 (460 hp) – each of which was evaluated during our study.

On each harvested site, we targeted observing 30 truckloads of screened grindings being produced. During this production, we performed a work sample of the grinder and screen on 2-minute intervals to document machine activities and obtain estimates of mechanical availability, utilization, and causes of delays. For each truck loaded with screened grindings, we recorded the total loading time and the number of loader bites to feed the grinder to obtain a full truckload. Truck payload was obtained from mill receipts.

Table 1: Treatments evaluated with grinder systems using screens to harvest logging residues.

Treatment	Grinder Size	Harvest Type	Weeks Since Harvest
1	Large (Peterson 4700B)	Roundwood (Clearcut)	4
2	"	"	8
3	"	Chipping (First Thin)	4
4	"	"	8
5	Small (Peterson 2400)	Roundwood (Clearcut)	4
6	"	"	8
7	"	Chipping (First Thin)	4
8	"	"	8

During the loading of each truck, we obtained samples from three material streams – (1) after grinding and before screening, (2) after screening (acceptable material), and (3) after screening (rejected, fine material). One sample of acceptable materials from the screen was collected for each load. The other two material streams were sampled for every fourth load. In all cases, composite samples were taken to produce a representative sample of each truck load. This was accomplished by combining several small samples from throughout each load and mixing them into one large composite sample. From each composite sample, a grab sample of approximately 1 kg was collected, bagged, labeled, and immediately weighed on-site to determine the field weight. These bagged samples were returned to the lab where they were dried at 105^0 C for 48 hours. Dried samples were then weighed and dry weights used to calculated field moisture content at time of grinding.

After drying, bags were randomly selected from each harvesting treatment for further analysis. These bags were fractioned, with roughly one-eighth of the sample processed through a 1mm screen Wiley mill and transferred to the University of Georgia Plant, Soil, and Water Lab for determination of energy, ash, and nutrient concentrations.

To measure fuel consumption during the study, we installed a GPI inline fuel meter on the fuel tank used to supply the woods equipment and recorded the fuel use each day during the study as possible. These data were later matched with the data obtained for number of truckloads, truck payloads, hours of operation, and tons produced to permit evaluation of fuel consumption on the operation.

Horizontal grinders rely on square "hammers" to shred the woody material. Over time, these hammers begin to dull and must be replaced for continued use – costing time and money. Hammer wear is a function of the feedstock material and is variable. In this study, hammers were replaced in the grinder at the start of each treatment unit and hammer wear was tracked throughout that treatment. When the hammers needed to be replaced, the number of loads associated with that set of hammers was noted. In this way, loads per set of hammers could be compared between the different treatments.

Ownership and operating costs for the grinder and the screen were estimated using data shared by our industry cooperator along with utilization, fuel consumption, and hourly production data obtained during the study. Using the estimates of total hourly costs, we evaluated the cost per ton (field moisture content), cost per ton (dry), and cost per BTU for screened grindings loaded in the woods.

PROJECT STATUS

The first round of field sampling commenced mid-April 2011. Half of the treatments have been sampled at this time. Some preliminary data and analysis from this round are expected to be available during the COFE Conference in June. Following the conference the remainder of the treatments will be sampled before the end of the summer season. Final results for all treatment groups will be completed by year-end and readers are welcome to contact the corresponding author for results if they are interested.

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APPLYING STATISTICAL PROCESS CONTROL TO FELLER BUNCHERS IN MAINE

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ABSTRACT

This case study applies the concepts of statistical process control (SPC) to better understand variability of forest harvesting operations and is based on data provided by a forest management company in Maine. Study data consisted of actual harvest records collected over a period of 20 months from two feller bunchers operating on 30 tracts throughout Maine. The productivity of each machine was evaluated over the entire period using Shewhart 3σ control charts. Control chart centerlines were estimated using the overall process mean and variability in the data was estimated using three estimates of σ based on the average moving range, the median moving range, and the overall process standard deviation. Control limits calculated using the average moving range and the median moving range provided similar results, but control limits based on the standard deviation proved to be too wide. Overall, the approach to understanding harvesting operations using SPC shows great potential for loggers and forest managers. The control charts highlight the level of variation operations managers must work with on a daily basis and, eventually, may be a valuable tool for decision making. Many challenges, primarily related to methods of data collection, still need to be overcome for SPC to be widely used in forest operations.

INTRODUCTION

A forest harvesting operation is a collection of interacting processes that convert standing trees into primary wood products. In this regard a forest harvesting operation, particularly one that is fully mechanized, is analogous to an industrial mass-manufacturing plant (Rajala 2003). The major difference is that instead of the raw material being transported to the factory for processing, the “factory” must move to and through the raw material. This is a considerable disadvantage for managing forest operations as there is very little control over environmental or material inputs.

In mass production, where processes are generally controlled and consistent, it has long been recognized that the economic impact of even small variations in process output can be severe. Therefore, many manufacturers have adopted a scientific approach to quality management which is now known as statistical process control (SPC). The primary objective of SPC is to bring routine processes into a state of statistical control where, through the use of past experience, one can predict how the phenomenon may vary in the future.

Forest operations managers have been slow to adopt SPC for a number of valid reasons, mostly related to the variability of inputs. SPC is more common in the wood products industry (Cassens *et al.* 1994, Young and Winistorfer 1999, Young *et al.* 2007), and very few studies have attempted to integrate SPC with forest operations (Coup 2009). The overall objective of this research was to demonstrate the use of SPC in forest operations. The specific objective of this study was to use SPC Phase I analysis to evaluate multiple control chart limits for two feller bunchers from whole-tree harvest operations.

SPC BACKGROUND

Critical steps of SPC include development of control charts and establishment of control limits. There are two distinct phases in control charting. Phase I estimates the unknown control parameters of the process (De Mast and Roes 2004) and Phase II analyzes the process in comparison to the control baseline as future records are collected (Chakraborti *et al*. 2009). In Phase I, historical critical measurement observations from a process are assessed to determine the natural variation of the process and to develop control limits. The control chart is used as an analytical tool to explore and understand the process behavior and to identify the limitations of natural variation within the process. This is achieved through a process that includes collecting an initial sample of process data, plotting a process parameter on a control chart and establishing control limits for the parameter. After plotting and establishing control limits, out-of-control (OOC) observations can be identified based on the limits set. Variability within the control chart limits is considered natural variation and observations falling outside the control limits are considered out of control resulting from special causes of variation. The procedure continues by indentifying and correcting sources of OOC observations, and recalculating control limits (Montgomery 2009, Chakraborti *et al*. 2009). Under ideal conditions, the process is repeated so that only natural variation of the parameter remains (Chakraborti *et al*. 2009). Often, several parameters are tracked for a single process.

It is important to emphasize that not only are the data adjusted to be in-control during Phase I analysis, but the process itself must also be systematically controlled through engineering and operating personnel before entering Phase II (Montgomery 2009). The greatest challenge in Phase I analysis is to estimate control parameters based on observations from the initial sample that are robust enough to identify the presence of OOC observations within the initial sample (Boyles 1997, Bryce *et al*. 1997, De Mast and Roes 2004). Control parameters can be calculated using numerous methods but they are all based on the mean, μ, and an estimate of variability, usually the standard deviation, σ. Once the process has been brought into a state of control, the control limits become the definition of statistical control for that process.

Phase II is more straightforward than Phase I as the focus shifts to examination of individual values as they are collected to verify whether the process is still in statistical control. The emphasis in Phase II is quick and accurate identification of special causes of variation in the active process so that corrective action can be taken to prevent economic loss. Equally important is the prevention of economic loss associated with taking action on natural process variation.

The literature describes three approaches to developing control charts using data types similar to those from this study. The first is a Shewhart individuals chart, more commonly known as a moving range chart. The standard approach is to use the average of the moving range, $\overline{MR}\ (X_k)$, typically of span size n =2, (Nelson 1982, Duncan 1986) where the moving range of span 2 at time t for sample X_k of size m is defined as:

$$MR_t(X_k) = \left|\left(X_t - X_{t-1}\right)\right| \quad \text{for } (t = 2, 3, \dots, m) \qquad (1)$$

and the mean of the moving ranges for sample X_k as:

$$\overline{MR}(X_k) = \frac{\sum_{t=2}^{m} \mathrm{MR}_t}{m-1} \qquad (2)$$

Essentially this method of estimating variability, σ, depends on arbitrarily creating small subgroups in order to capture short-term variability. Although other group sizes (n >2) can be used, using the moving ranges of span size =2 to estimate σ is justified as representing the short-term process variation, as a sample or rational subgroup would, while also preventing the estimate from being influenced by a lack of control in the data due to special causes (Nelson 1982, Duncan 1986, Wadsworth *et al*. 1986). The control limits in the present case were calculated using:

$$M(X_k) \pm \frac{3\overline{MR}(X_k)}{d_2(2)} \qquad (3)$$

Where X_k – Denotes the initial sample

$M(X_k)$ – Denotes the mean of the initial sample

$\overline{MR}(X_k)$ – Denotes the mean of the moving ranges (of span size =2)

$d_2(2)$ – Is a constant based on moving range span size that makes $\overline{MR}\ (X_k)$ an unbiased estimator of σ (1.128 for span size =2).

The second approach, using the median of the moving range, results from a problem associated with moving range charts that are based on averages. Because the moving ranges are averaged, observations that differ widely because of special circumstances can inflate the estimate $\overline{MR}\ (X_k)$ and lead to a poor estimate of variability (Bryce *et al*. 1997). Because each observation comprises two moving ranges, large isolated outliers influence the estimate of σ (De Mast and Roes 2004). As such, several authors have proposed using the median rather than the mean of the moving range (Bryce *et al*. 1997, Wheeler 2004, De Mast and Roes 2004). Control limits using the median moving range estimator for σ are given by

$$M(X_k) \pm \frac{3MMR(X_k)}{0.954} \qquad (4)$$

Where X_k – Denotes the initial sample
$M(X_k)$ – Denotes the mean of the initial sample
$MMR(X_k)$ – Denotes the median of the moving ranges (of span size =2)
0.954 – Is a constant used to render $MMR(X_k)$ an unbiased estimator of σ

In using the moving range to calculate the control limits we assume that the process for each machine is continuous over all tracts and breaks in operation throughout the time span of the dataset. In the case of feller bunchers, it also assumes that the harvesting process remains largely unchanged when implementing different prescriptions.

A third approach, advocated by Ryan (1989) and Cryer and Ryan (1990), for in-control processes, uses the standard deviation of the initial dataset in order to estimate σ. The control limits in this case are calculated as

$$M(X_k) \pm \frac{3S(X_k)}{c_{4(K)}} \qquad (5)$$

Where X_k – Denotes the initial sample
$M(X_k)$ – Denotes the mean of the initial sample
$S(X_k)$ – Denotes the standard deviation of the combined individual observations in the initial sample
$c_4(k)$ – Is a constant based on the total number of individual observations in the initial sample that makes $S(X_k)$ an unbiased estimator of σ (given by $\left(\frac{4n-3}{4n-4}\right)$ for n >25)

The standard deviation is a long-term estimate of variability since it measures the dispersion of every observation within the initial sample over the entire time interval (Rigdon *et al*. 1994, Bryce et al. 1997). It is more sensitive to special causes in the data than Equations 3 and 4 because the required squaring of the individual value's deviations causes outliers to substantially inflate the estimate of σ (Rigdon *et al*. 1994, Bryce *et al*. 1997, Montgomery 2009). As a result Shewhart (1931) determined that the standard deviation of the individual observations results in control limits that are unnecessarily wide. Rigdon *et al*. (1994) recommended using the control limits based on Equation (3) rather than the limits based on Equation (4) for Phase I analysis. Cryer and Ryan (1990) recommended that both control limits (3) and (5) be calculated and compared for a given series of observations. If both control limits agree reasonably well, they felt that the practitioner could be fairly confident that the series was in control. However, if the process was not in control, then the $\frac{S(X_k)}{c_4(k)}$ estimate would be substantially inflated, and consequently, the control limits would be much wider than they should be (Braun and Park 2008).

METHODOLOGY

The production and operations data used in this study were not collected for the express purpose of implementing an SPC program, but were provided to demonstrate the potential for use of SPC techniques in forest operations. The dataset included production and operation records for two feller bunchers from a single company. Productivity was determined as bunches per productive machine hour as described below.

The machines were used in predominantly single-shift, whole-tree harvesting operations on 30 tracts throughout Maine between September 2005 and May 2007. Each machine operator completed daily shift reports to record production and to describe operating conditions. Production was tracked on a shift basis using tally meters and it was recorded as total bunches cut. Only a single silvicultural prescription was executed per shift and no clear cutting operations were conducted during the period of data collection.

Production in this study is based on discrete data, so it provides only a coarse assessment of production since the actual volume in each bunch varies. Our assumption is that the operators fully utilize the accumulating capacity of their respective machines on each cycle so that bunch count becomes a suitable proxy for production. All productive observations were converted to productivity estimates based on productive machine hours (PMH). Control charts were developed for each machine based on productivity estimates per day as described above. Individuals charts (also known as Shewhart X-charts or i-charts), were then used to evaluate the operating productivity of each machine over time. In this study all three types of control limits described above were calculated based on Equations 3, 4 and 5. The limits were compared to one another to assess their performance and to identify if special causes of variation exist within the dataset.

RESULTS AND DISCUSSION

The goal of Phase I analysis is to ensure that the process is operating at or near an acceptable level under only natural causes of variation, with no special causes present, and to estimate the parameters of the in-control process. An operational summary for machine-level parameters is provided in Table 1. Shewhart individuals charts using three control limits were developed showing productivity for each machine as shown in Figure 1.

The control charts, and specifically the control chart limits, clearly express the level of productivity variation operations managers must work with on a daily basis. All methods were characterized by frequent spikes in operating productivity with very few instances where the felling process exhibited stable, consistent output over any substantial period of time. As shown in Figure 1, Equation 4 had the narrowest range, while the limits based on Equation 5 had the widest. The wide range in control limits based on Equation 5 may indicate that the process is not in control as noted by Braun and Park (2008). Differences between control limits based on Equations 3 and 4 were only minor and most likely the result of Equation 3 being more sensitive to the variability within the datasets by estimating σ by the mean of moving range rather than the median. It is important to note that although the data used to compute the control limits may be

OOC, the Equation 3 and 4 limits obtained are still robust enough to detect that lack of control within individual observations.

Table 1: Operating summary for two feller bunchers from September 2005 to May 2007.

	Feller-buncher 1	**Feller-buncher 2**
Machine make and model	TIGERCAT 845B	TIGERCAT 822
Year	2002	2003
Equipment hours at beginning of study	5406	429
Number of operators	3	7
Total days of productive operation	310	331
Number of tracts operated on	21	13
Average fuel consumption (liters/shift)	269	256
Average number of bunches cut per shift	70.9	61.2
Average number of operating hours per shift (hh.h)	8.9	9.0
Average equipment hours per shift (hh.h)	8.8	8.3
Average shift time (hh.h)	10.1	10.4
Average utilization rate (%)	80.6	75.6
Number of terrain types operated on	8	11

Based on the vast number of potential input variables that could have affected the performance of individual records it was difficult to determine underlying special causes for many of the OOC observations. Several of the OOC observations that fell below the LCL had recorded notes that could at least help to explain why the productivity was low (e.g. unfavorable operating conditions, or working on unproductive tasks). However, it is important to emphasize that while many of the downtime and delay details recorded by the operators may help to explain that shift's utilization rate, it does little to explain the productivity of the machine when operating - which is the variable of interest.

In many instances sustained drops in machine productivity could be linked to particular tracts. For example, FB2 productivity was reduced from an average of 7.8 bunches/PMH to 5.2 bunches/PMH after a tract change on 4/24/07 (Figure 1B). This potentially can be attributed to harvesting on rocky terrain. Operator notes indicate several mechanical problems throughout this time and poor utilization rates, particularly on the latter OOC shifts.

For observations that exceeded the UCL, there was less information about the operating methods and conditions that could be used to identify what contributed to the increased operating productivity. Surprisingly, several of the operating productivities exceeding the UCL were associated with very low utilization rates. Several cases were again identified where higher productivities occurred on a particular tract. While none of the observations signaled, FB1 had higher than average productivity on a tract from 2/9/07 to 2/22/07 while conducting an OSR on flat terrain (Figure 1A). Productivity for FB2 was also consistently higher on a tract from 6/10/06 to 6/29/06 while conducting an OSR on terrain generally classified as wet/rocky/flat (Figure 1B).

Figure 1. Individuals control chart of operating productivity for two feller bunchers – (A) FB1 and (B) FB2 – with control limits calculated using Equations (3), (4) and (5). OOC observations (solid points) were identified based on Equation (4) control limits. A frequency distribution of the data is included on the right. Indications of tract changes are also included.

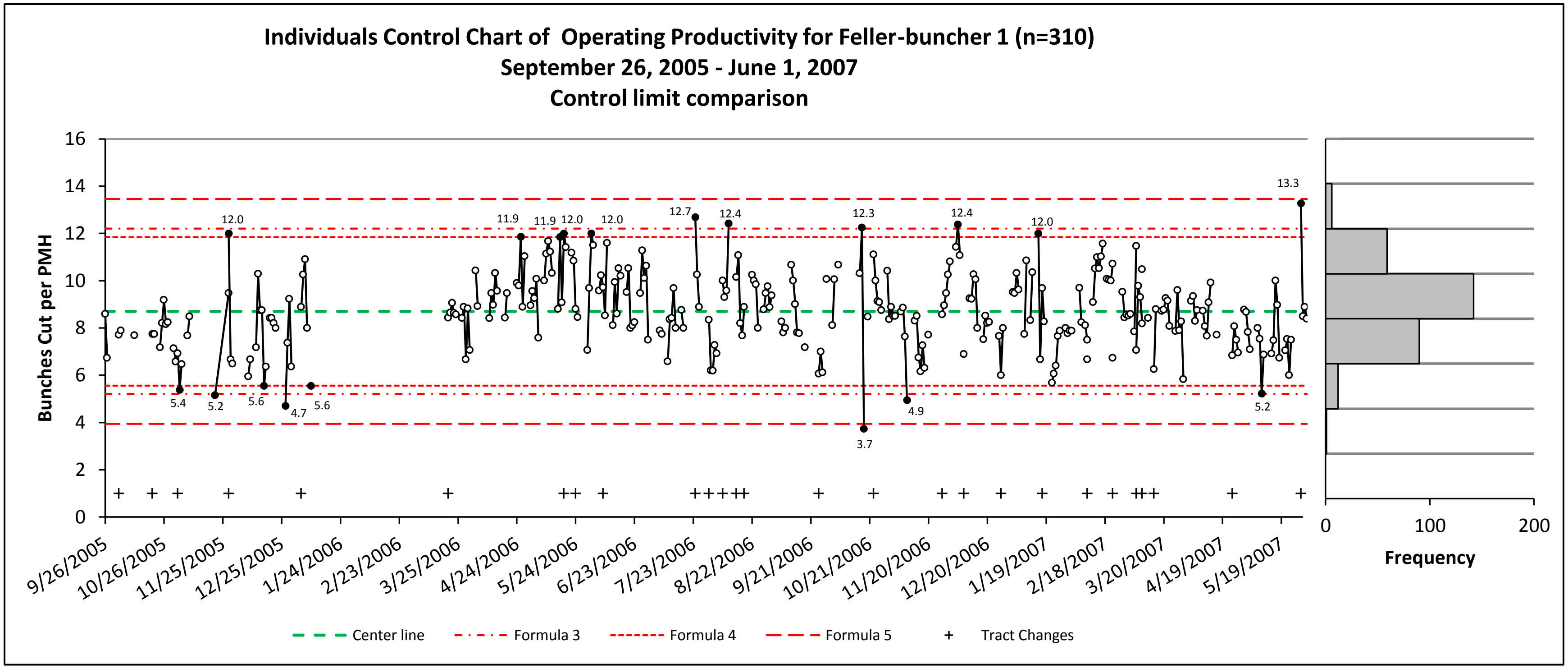
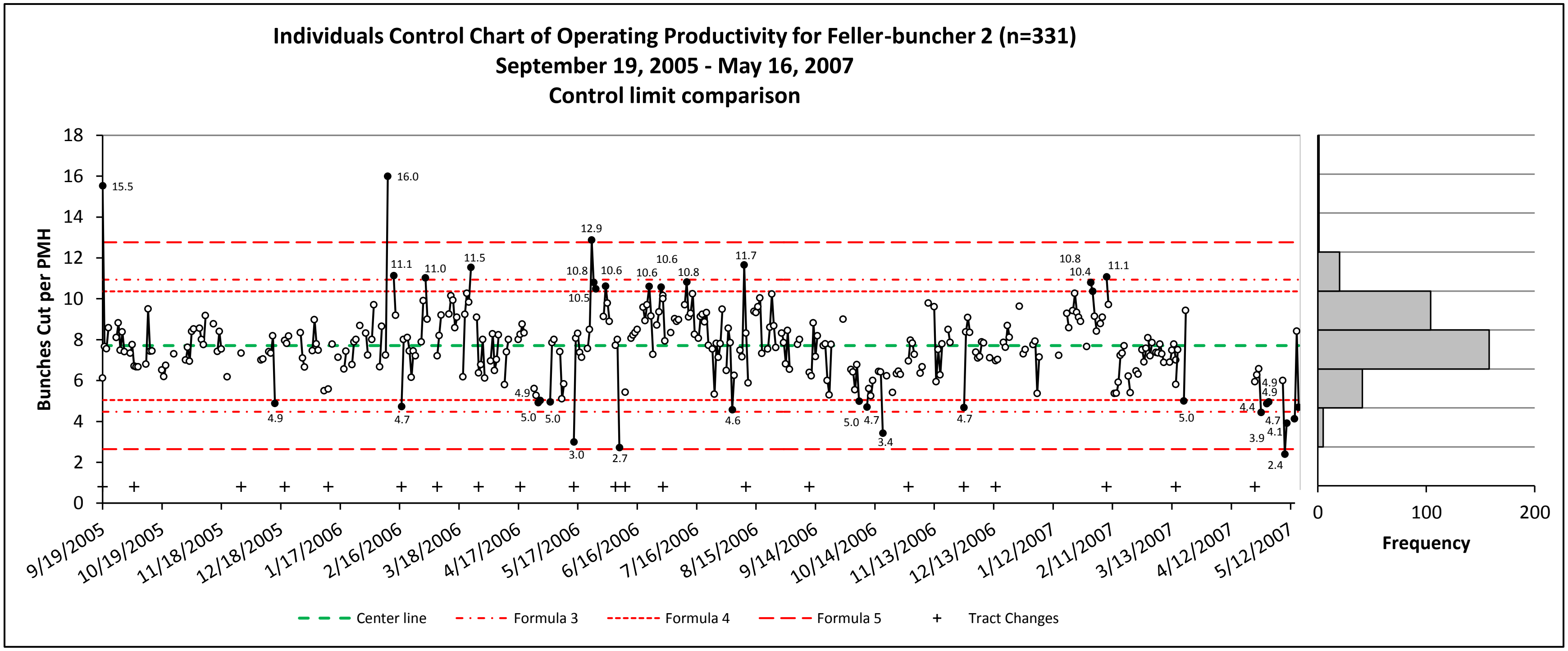


Figure 1A



Individuals Control Chart of Operating Productivity for Feller-buncher 2 (n=331)
September 19, 2005 - May 16, 2007
Control limit comparison
Bunches Cut per PMH
Frequency
Center line
Formula 3
Formula 4
Formula 5
Tract Changes

Figure 2B

One special cause of variation identified was the presence of several production values identified by operators as “estimated” on the production and operations records. Presumably this means that during active operations, tally meters were not used in a consistent manner and production was instead estimated at the end of the shift. All but one of these estimations resulted in operating productivity values that exceeded the UCL. As part of the Phase I analysis all estimations of productivity should be excluded from the dataset as they do not accurately reflect the actual process behavior and bias the control parameter estimates. Because of the structure of the dataset used in this study, there was no way of easily filtering out these estimated values.

While the charts identified several OOC observations, the distinction between common cause and special causes of variation remains largely context dependent. Applying the strict SPC definitions of natural and special cause variation can result in some confusion in the context of forest operations. For example, the record for FB1 on 12/27/05, noted that “snow covered the trees” which would likely explain the OOC operating productivity of 4.7 bunches per PMH for that shift. In the strict sense this should probably be considered a special cause of variation. However, snow in Maine is a common winter occurrence and there is little that can be done to eliminate the effects of a deep snow on feller-buncher productivity. Perhaps, a separate chart each season would be beneficial to account for weather conditions. Of greater importance for SPC is the effect of terrain on productivity which is difficult to take into account. In the broad analysis conducted here, the data from different sites were lumped together. While some surprises were seen, as noted above, the effect of difficult terrain is to reduce the volume of wood delivered to the log landing and to increase maintenance problems. Over time and with consistent effort, producers could develop charts that were tailored to specific types of terrain.

CONCLUSIONS

Statistical Process Control has the potential to be used as an approach to understanding and reducing the variability of forest harvesting operations. The long term focus of an SPC approach to process improvement offers a means of understanding harvesting processes that cannot be easily achieved through the traditional case study approach to forest operations research. Based on the control limit comparison conducted in this study there appears to be little advantage in using the median of the moving ranges over the more commonly used mean of the moving ranges for Phase I analysis. Differences between the two control limits were mostly the result of outliers within the datasets, many of which would be removed due to their suspected association with special causes. The focus of future research in applying SPC to forest harvesting operations should be on developing a methodology that will consistently yield useful results for improving the harvesting process. It would also be helpful if data collection could be automated to avoid intrusion with the process of harvesting and skidding logs.

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TRANSPIRATIONAL DRYING EFFECTS ON ENERGY AND ASH CONTENT FROM WHOLE-TREE CHIPPING OPERATIONS IN A SOUTHERN PINE PLANTATION

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ABSTRACT

Newly announced North American bioenergy projects will likely increase the demand for woody biomass substantially over the next five to ten years. High harvesting and transportation costs for woody biomass from forests are commonly identified as key constraints to expanding this new industry and meeting expected wood fiber demand. In addition to a cost-competitive feedstock, wood energy facilities prefer drier raw material to maximize energy content and cleaner material with less dirt or grit to minimize the ash remaining after combustion.

We examined extended transpirational drying times of felled trees to study their correlation with moisture, ash, and energy content. We compared production rates and material properties for three drying treatments of felled trees in a 14-year old planted loblolly pine stand: (1) drying in the field for approximately eight weeks, (2) drying in the field for approximately four weeks, and (3) freshly felled (or green) trees. A range of operational variables including fuel consumption, knife wear, chipper productivity, the number of stems per linear foot of trailer, and tons per linear foot of trailer were also compared.

INTRODUCTION

Higher market prices for fossil fuels as well as proposed policy changes to support renewable energy and reduce carbon emissions have recently led to a large number of bioenergy projects being announced which will consume woody biomass. Projects announced for North America as of September 2009 will substantially increase wood energy capacity and will potentially consume more than 60 million green tons of wood biomass feedstock (RISI 2009). A survey of top state forestry officials recently identified high harvesting and transportation costs for woody biomass from forests as the top constraint to expanding this potential new industry (Aguilar and Garrett 2009).

Harvesting systems that could supply these renewable energy facilities already exist, but each operates with a different incoming feedstock (residues, understory, standing trees, etc.) and produces a product that differs in its characteristics (moisture content, particle size and uniformity, ash content, etc.). Few studies have examined methods that could improve woody biomass characteristics in the field to add value to the feedstock required by bioenergy facilities.

It is important for woody biomass feedstock to have low moisture content to increase its energy value (BTU). A greater energy value results in greater burning efficiency. The amount of ash content is a critical characteristic for woody biomass feedstock. Woody biomass with high ash content is considered to have poor quality because it results in poor combustion performance and additional disposal costs (Sarenbo 2009). The biomass harvesting system employed, type of woody biomass material, and the manner and duration of how woody biomass is stored or piled on-site are all factors affecting moisture and ash content (Pettersson and Nordfjell 2007).

The timber harvesting and wood supply chain in the United States is globally competitive and is well positioned to add woody biomass to the list of products it delivers. However, there are some significant issues to be addressed to support these new wood-using industries. Most traditional forest industries (paper and building products) purchase their raw material today on a green ton basis. In fact, several states in the US South require exclusive use of the green ton as a measurement method when stumpage is purchased on a pay-as-cut basis from landowners. There are several advantages to this method, including ease of automation of the weighing of trucks and the incentive a green ton basis provides to logging contractors to deliver fresh wood to markets. Fresh wood provides higher pulp and tall oil yields in most pulp processes as well as limiting checking and blue stain issues with sawtimber.

Wood energy markets (biorefineries, pellet manufacturers, wood-fired electric plants, and wood to liquid fuel processes) are often interested in procuring raw material that has less moisture content than green wood to obtain a higher energy (BTU) value. Each 10% reduction in moisture content can increase the BTU value of the wood by approximately 850 BTU (Ince 1979). Freshly felled trees have a moisture content of approximately 50% (wet basis) – this varies somewhat by species – but if allowed to dry for four weeks before delimbing and processing, moisture content can be reduced to 30-35% (Stokes *et al.* 1993). This delayed delimbing and bucking is known by several names but we will refer to it as *transpirational drying*. Wider use of transpirational drying could have several significant benefits for wood energy markets. For example, it removes moisture content without consuming any wood or fossil energy. It also eliminates the need to transport the water contained in green material, thus increasing the net energy content of each truck payload. This could lead to fewer truck trips needed to move the same energy content to markets, thus saving fuel and further improving net energy ratios. On the other hand, drier material is commonly reported by logging contractors to drastically increase the need to sharpen chipper knives which increases maintenance costs and reduces knife life. This can also reduce chipper productivity.

While reducing moisture content is critically important, keeping ash content low in combustible woody fuels is also important. This study assesses if increased drying times are correlated with reduced moisture content and increased ash content.

METHODS

The study was conducted from August to October 2010 on a 14 year-old loblolly pine stand in Jones County, Georgia. Trees were felled in rows and allowed to transpirationally dry eight and four weeks prior to chipping. Green stems were felled in conjunction with the chipping operation. A 600 horsepower Morbark 40/36 drum-style chipper was used to chip the material.

Figure 1: 600 horsepower Morbark 40/36 drum-style chipper.

Climate data, including daily temperature and rainfall, were obtained from the National Weather Service for the drying periods. Additionally, a rain gauge located on the study site was used to monitor weekly rainfall during the drying periods.

To quantify production impacts, common work sampling and time study methods were used to record data on the harvesting system (Baker, et al. 2010, Westbrook, et al. 2007). Continuous activity data were recorded separately for the three treatments. Machine activity codes were recorded for the chipper and knuckleboom loader on-site every two minutes for the duration of the field study to establish mechanical availability, utilization, and sources of delay. Loading times and load weights for each truck load were also recorded.

During the loading of each truck, a 6" diameter PVC pipe with an elbow was used to collect samples from the chip stream. Samples were collected several times during the loading of a van and mixed for a composite sample. From this sample a 4-5 lb sample of chips was collected and placed in a kraft paper bag. The bag was immediately weighed to determine the field (or wet) weight of chips. The bags were then transferred to a 105 degree C oven for 24-48 hours and reweighed to determine the field moisture content.

After drying five bags were randomly selected from each harvesting treatment for further analysis. These bags were fractioned, with roughly one-eighth of the sample processed through a 1mm screen Wiley mill and transferred to the University of Georgia Plant, Soil, and Water Lab for determination of energy, ash, and nutrient concentrations. The remaining seven-eighths of the bag was transferred to a chip classifier. The sample was oscillated in one dimension for ten minutes to separate the chips based on their length. Four round-holed classification screens were used to determine the size distribution: 45mm, 15mm, 7mm, and 3mm. Foliage was removed from the sample and weighed separately. Bark was separated and weighed separately from wood for chips collected in the 45mm, 15mm, and 7mm trays.

Production data were compared using analysis of variance with Tukey's range test used for means comparison. Wood chip data were limited to five samples per treatment, necessitating use of Kruskal-Wallis exact test for comparison. Work sampling data were analyzed using chi-square test to look for differences in the distribution of work amongst categories.

RESULTS AND DISCUSSION

Average temperature for the 8 week drying period was 76^o F and 71^o F for the 4 week drying period. The amount of rainfall obtained from the National Weather Service and verified by the on-site rain gauge was 7.1 inches for the 8 week drying period and 5.2 inches for the 4 week drying period.

Moisture content of the samples varied significantly based on the length of transpirational drying (Figure 2). Each subsequent four-week drying period significantly decreased the moisture content of chips produced ($p < 0.05$), with the largest reduction occurring following the first four-week period. The reduced moisture content had a significant impact on the weight of material able placed in chip trailers (Figure 3). The field weight of chips per linear foot of trailer decreased significantly with each subsequent four-week drying period ($p < 0.05$). When examining the volume of materials in the trailer on a dry-ton basis, there was no significant difference in the tons per linear foot. Thus the volume of material in the trailer appeared to be equal across the treatments, although the weight was reduced.

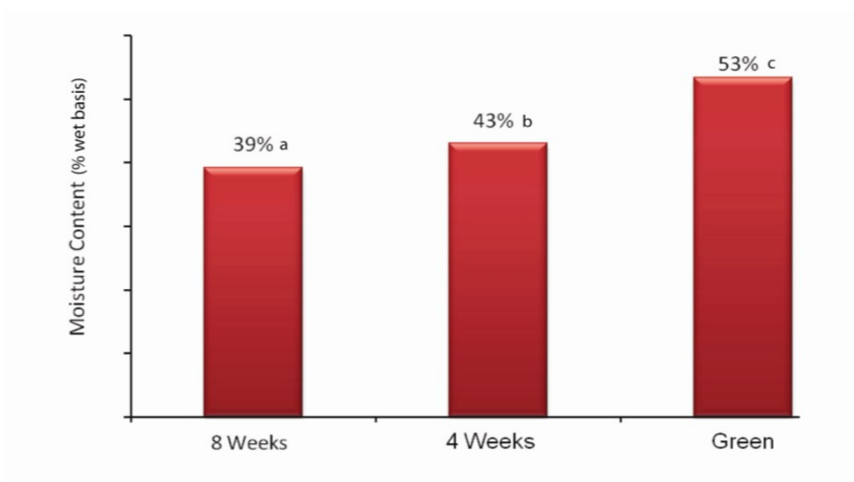

Figure 2: Moisture content of wood chips harvested fresh and allowed to dry four and eight weeks. Different letters indicate significantly different values ($p < 0.05$).

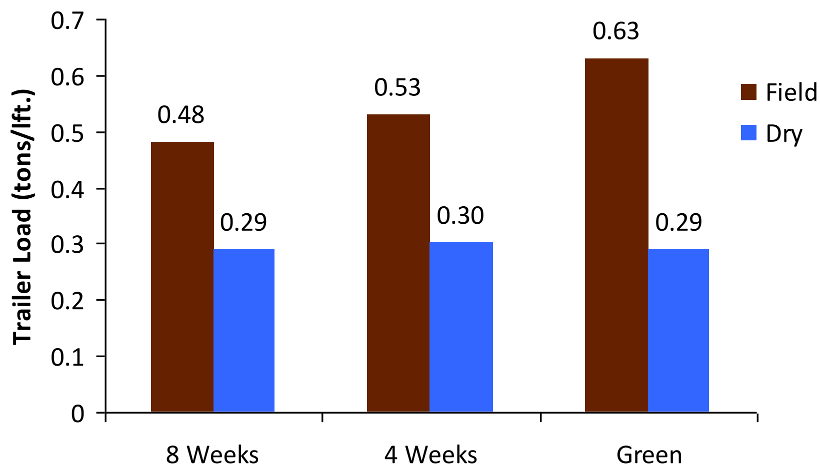

Figure 3: Average weight of chips per linear foot of loaded chip van from stems chipped green, and stems allowed to dry four and eight weeks respectively.

Age of the material had a significant impact on the productivity of the chipper as measured by field tons produced per hour (Figure 3). A significant difference was not observed between material dried eight weeks and material dried four weeks, but chipping productivity of both was lower than for green materials ($p < 0.05$). Converting the material produced to a dry ton basis using the measured moisture content reveals the chipper productivity also varied as measured by dry tons produced per hour; however, now the productivity from the green treatment is significantly lower than from either of the dried treatments (Figure 4). Thus, the chipper is able to produce a slightly (12%) greater volume of material per hour if the feedstock is dried, but it cannot produce an equal weight of material per hour.

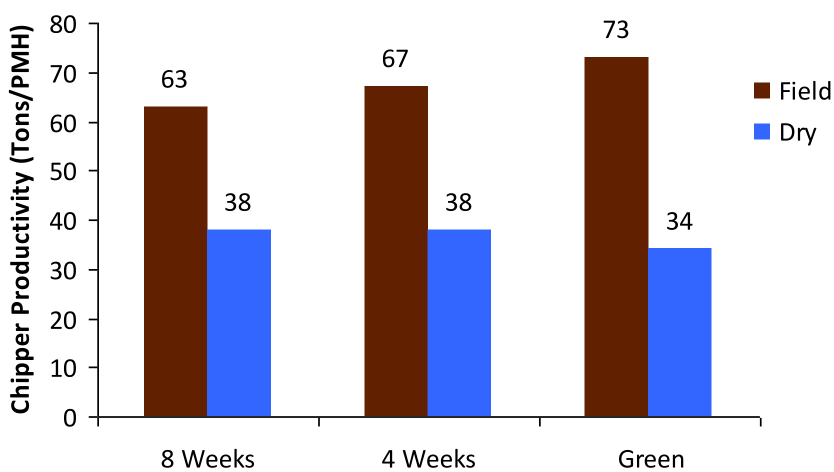

Figure 4: Productivity in green and dry tons produced per productive machine hour of a chipper processing freshly cut stems and stems dried for four and eight weeks respectively.

Utilization data show that the chipper was able to spend a significantly higher percentage of its time chipping in the oldest treatment (eight weeks) compared to either the four-week old or green material (Figure 5, $p < 0.05$). Most of the shift came from time spent working on the chipper in the fresh and four-week old treatment. Given the short timeframe of this study, it is uncertain that this result would be repeated over a longer time period.

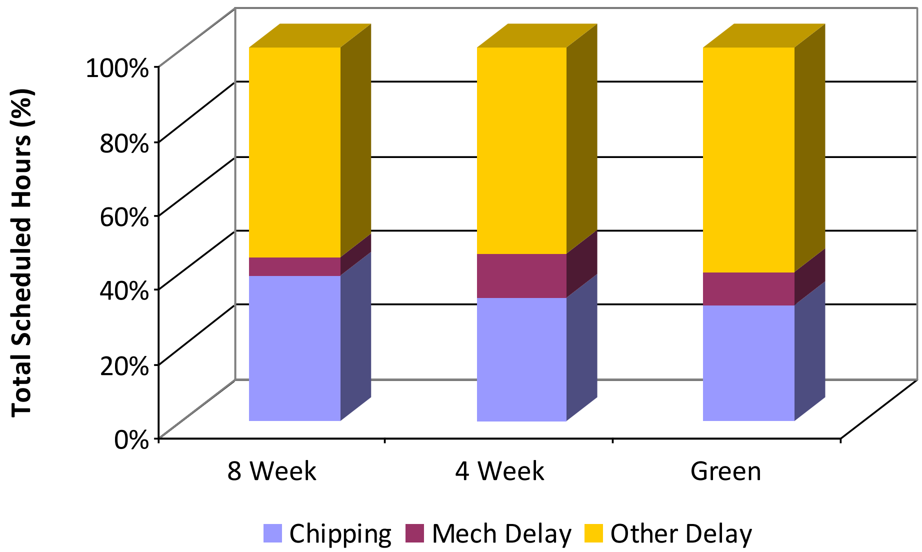

Figure 5: Distribution of total scheduled hours spent chipping the freshly felled four-week old and eight week old treatments.

Insufficient fuel measurements were taken to allow for a statistical test of fuel consumption between the treatments, but observed fuel consumption did not vary substantially (Figure 6). The duration of the study also did not require a sufficient number of knife changes in any treatment to allow for statistical analysis. Both the eight and four week treatments changed knives once during the duration of the study, after ten and fifteen loads respectively, while the knives were not changed during chipping of the green treatment (28 truck loads).

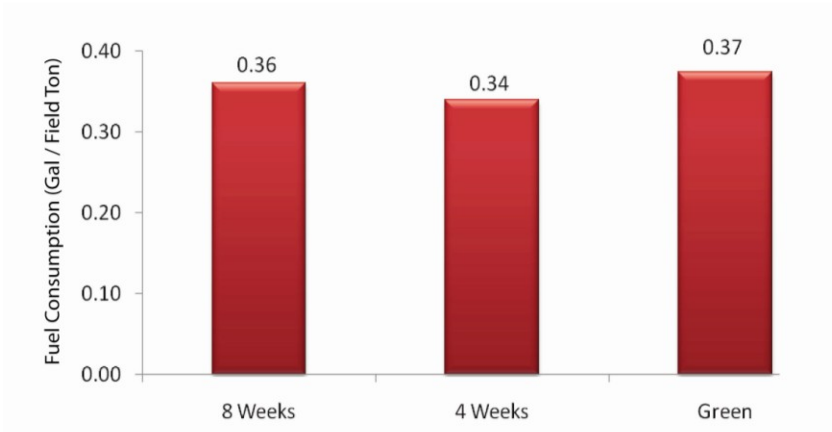

Figure 6: Fuel consumption of the chipper while processing stems harvested fresh and stems which had been allowed to dry for four and eight weeks, respectively.

There were visually noticeable differences in foliage content between dryer stems versus green stems. There were more pine needles on the ground in thinned rows and on chipping decks for in areas where stems had dried (Figure 7).

Figure 7: Pine foliage within rows for dried material (left) versus green material (right).

No significant differences existed between either energy or ash content for chips in the three treatments (Table 1). Energy content for chips are consistent with previous tests on pine feedstocks. Ash contents of less than one percent are also in-line with previous studies on field-run whole-tree chips (Baker, *et al*. 2011).

Table 1: Energy and ash content of wood chips harvested fresh and harvested after drying four and eight weeks, respectively.

Treatment	Energy Content (BTU/o.d. lb)	Ash Content (% o.d. wt)
Green	8200	0.69
Four Weeks	8330	0.54
Eight Weeks	8160	0.60
Average	**8230**	**0.61**

SUMMARY

Moisture content was reduced from 53% for green material to 39% for material allowed to transpirationally dry in the field for eight weeks in late summer. Each four-week drying period resulted in significant reductions in moisture content. There was less truck payload associated with dryer material. The green weight of chips per linear foot of trailer decreased significantly with each subsequent four-week drying period.

The chipper productivity study indicated that the chipper is able to produce a greater volume of material per hour if the feedstock is dried, but it cannot produce an equal weight of material per hour. Fewer tons were produced and loaded for dryer material, which could result in producing material with higher energy content, though there were no significant differences in BTU values for the three treatments. The small sample sizes for BTU values might explain this lack of difference.

ACKNOWLEDGEMENTS

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THE PEOPLE SIDE OF TIMBER HARVESTING

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ABSTRACT

The common belief is "your people are your most important asset", but when it comes to safety and moving the wood in a timely fashion, "the people who ***lead*** your people are your most important asset."

More times than not, thoughts and philosophies behind strategies in motivation, and employee engagement fall by the wayside once a harvesting crew enters the woods. The forest supply chain is not only made up of products, but living breathing human beings who spend a better part of their lives in the woods. These professionals are NOT immune to the principles of human nature. More attention needs to be paid to that when speaking of strengthening the forest value chain.

Safety in the woods is vital, and all the hardhats and steel toed boots will not save a disengaged employee from the perils of an accident on the job.

A conscious decision needs to be made by owners of timber harvesting companies, to build employee engagement through training. Strengthening crew supervisors in the areas of communication, leadership, team building and motivation will not only improve production, but create a safer work environment.

Leadership training in the corporate world is an everyday consideration to strengthen the bottom line. It is common knowledge that employee engagement will eliminate costly mistakes. In the woods, being on the cutting edge means acquiring new equipment. There needs to be an awareness and understanding that the people side of timber harvesting is equally important as a well planned preventative maintenance schedule.

Loggers live in the urgent, blown hoses, equipment failure, and ever changing quotas. Planning and awareness of the basic psychological principles of motivation will give them a better understanding of every day human relations.

Keywords: Employee, engagement, leadership, safety, production

THE PEOPLE SIDE OF TIMBER HARVESTING

This paper is to raise awareness in the forest products industry of the value of strengthening the human side of timber harvesting.

The forest products industry has it down to a science. Certification shows that our industry cares for the indigenous people and the environment, making sure that the wood is as pure as it can be. The industry has been working hard to develop criteria to strengthen the purity of the path the wood takes to its final destination. It seems that most of the focus for improvement is on the product and the path, and not the people who move wood along that path. The strength of our industry lies on the backs of those who cut the wood, the loggers. In order to strengthen the chain where it matters most, more focus should be paid to strengthening the soft skills of management of those who hold up the industry, our loggers. This will strengthen the chain at the beginning, in the woods, right at the stump.

It all starts with a landowner who needs to communicate with a forester, logger or land management company and vice versa. There, in the woods, under a hemlock or maple, as their feet touch the ground and their mouths move to exchange information is where it all begins. The chain begins there, the chain of wood and the chain of communication, one that can be strengthened or weakened. One that can be used as an opportunity for education and relationship building, or relationship weakening, where words are shared and checked for understanding, or not. After speaking with the landowner, the forester or logger needs to communicate the harvest plan to the crew supervisor, and then he or she will convey that information to each crew member and trust that they will work to support the company in a way that strengthens the bottom line.

Every human interaction along the forest products chain is one that can be used for maximum potential, or one that can be treated as a casual means to an end. An awareness of the principles that govern good human relations needs to be interwoven throughout this chain that is so quickly called the forest "products" chain. The care and cultivation of people involved in timber harvesting is as important to the logging industry as the ideas of innovation that improve the technical side of our businesses. I have spent two years working as a training consultant, behind the doors of local, national and international companies, and six years in the logging industry. My unique perspective can only be gained by straddling the "edge", where corporate employee development meets logging crew development. I've had the unique opportunity to have one foot in the woods, and one foot in the boardroom, with regards to employee development, and I work hard to make leadership, communication and teambuilding skills available to those who could benefit most.

Every good business, whether in the corporate world, or not, needs to overcome hurdles when working to develop its people. These businesses deal with budget cuts, schedules, attitudes, and fears. To those who ask" What if I train this person, soak a lot of money into them and they leave?" I say, "What will happen if you don't, and they stay?"

Businesses are like families, they all have issues. It's the businesses that opt to deal with those issues that place themselves on the cutting edge. There are all sorts of struggles to overcome in order to train and work with employees to assure that businesses are getting the best return on their investment.

In the woods, the struggles are the same as those faced by traditional business, only magnified by additional stressors. Variables that are beyond a logging contractor's control, such as unpredictable markets, excessive regulation, weather, quotas, fuel prices, breakdowns and attitudes; attitudes exacerbate the already challenging situation. A logger from the state of Washington had this to say about employee engagement on the job.

"Employee comfort is of least most importance unless it is acquired as a freebie as a result of other policy changes. There is no goal setting, or set review period for raises. You are hired into a job title and there you stay at a given rate of pay. Hard work will get you advanced in stature. Whining and griping will get you canned. If you don't agree with these rules, then simply find a different line of work. That, in a nutshell, is the law of the land out here." He went on to say that usually any initiative would be regarded with suspicion as only a means to an end, benefitting the corporate entity only.

"Meetings, *Scmeetings*, who needs them? Just go into the woods and get the wood out!" was the reaction I got from a logger named David, as I worked to create a regular staff meeting schedule. Regular meetings, goal setting and reviews are the least of what needs to take place in the woods. Later, after he saw the impact the changes had on the crew, David gave me a heartfelt apology. The challenge here is to infuse our logging culture with these skills to receive maximum employee engagement. After all, the new global business reality is more production, faster and with fewer resources.

One of the biggest challenges in Maine's forest product industry is the difficulty we have attracting young people into the logging profession. One of the reasons is the lack of occupational prestige, as noted by Professor Andrew Egan's research project "Business and Employment Stability and Sustainability in the Logging and Forest Products Community of New England and New York" as well as one of the realizations gleaned from the Logger/Trucker Congresses conducted around the state of Maine by the Maine Forest Service and The Trust to Conserve Northeast Forestlands in 2008. More focus on employee engagement by strengthening leadership skills will strengthen the professionalism of the logging industry. Logging companies need to know that they have these training resources available should they want to access them. (Egan 2007)

Logging, by nature, is for the tough. While working in the woods one day, a crew member cut his hand on a chipper knife, not too serious, but requiring stitches. As he got in my rig to go to the hospital, but had to endure comments like "pull up your skirt" or "wrap it up and get back to work."So with regards to training, fears are heightened with the mere thought that if a logger exhibits buy in, he could be viewed as a traitor or someone who "needs to pull his skirt up". So, when analyzing what needs to happen with training, you have to take into account all the customary business struggles as well as the attitudes and traditions from a profession steeped in tradition.

TRAINING LEADERS IN THE WOODS TO IMPROVE SAFETY AND PRODUCTION

There is a whole wealth of value that comes from focusing on employee engagement. The equation I like to use is, US + CREW = TEAM. In this simple equation, crew leaders learn that creating a sense of team isn't just learning about the crew, but learning about themselves as well. This awareness is part of the secret to creating a strong "TEAM" which is the key to workplace or employee engagement. The true sense of the word is a little ethereal, but extremely valuable nonetheless. A crew supervisor may have great leadership skills but still need to understand how to use those skills to get the most out of his crew. Unlocking a harvesting crew's potential takes a leader who understands the principles behind inspiring their crew members to be the best they can be. It is his or her responsibility to understand that, and make it happen.

All of these principles have to do with the soft skills of management. Without "soft", the drivers of business success will always be less than what they could have been in the areas of leadership, communication, teambuilding, motivation, change management, and improved safety. Yes, analyzing the job, creating the harvest system to move the wood in the most technically sound way, is crucial to production. At the other end of the spectrum, and equally as important, is the emphasis on the human element of that production. To ignore that would be to make logging an even more dangerous profession than it already is.

In the woods safety is vital, and a great safety program is only as good as the employees who live it. Crew supervisors cannot demand safety, but need to inspire it. In response to mentioning his book on management in my blog, I was contacted via e-mail by Rodd Wagner a principle at The Gallup Organization and New York Times bestselling author to say this, "Thank you for your mention of *12: The Elements of Great Managing* in your column on employee motivation. You are absolutely right that companies can't force people to do everything they want them to do. There is a huge range of performance based on the engagement of the employee and the team."

Safety is a combination of tangible and intangible elements. The intangible is centered on the soft skills of management. These intangible elements are like invisible assets woven through the workday, workweek and work lives of all that belong to the crew. In order to understand the impact that these principles have on the work team, crew supervisors must learn that an engaged employee is a safer employee. Wagner went on to tell me, "As you mentioned, the implications of employee engagement for safety are astounding. I've spent some time reviewing OSHA reports on serious accidents. Although there is always some proximate cause of the accident -some failure to follow procedures - the reason behind that failure often appears to be a simple lack of vigilance or mindfulness of others, making engagement just as important as a hard hat or steel-toed boots."

Leaders in the woods are responsible for making the harvest job the safest it can be. Learning how to use the tools of engagement will improve the conditions on the job, and go beyond personal protective equipment.

Across the board, in the logging industry, there needs to be a blanket understanding that leadership skills are important in order to maximize production and safety. Whether a leader is leading one or ten crew members, if words are exchanged, those words can be handled mindfully to achieve the most benefit, for the leader, the crew and the company.

Crew supervisors generally get promoted for hard work and knowledge of the products and systems. This is the perfect time for training to take place. A logging company's most important asset is the leaders who lead their people. The industry has to create an influx of opportunities for leadership training on this level, before the damage of poor management can be done. Before production and safety are compromised. This is the window of opportunity where the groundwork can be laid for improved leadership skills in order to get the most out of crew members. Dwight Eisenhower once said "Leadership is the art of getting someone else to do something you want done because he wants to do it".

Adding prestige to the profession by boosting the attention to job satisfaction through employee engagement is priceless, whether a crew of two or five, in a company of fifteen or fifty.

Us

When working to understand the power of the employee engagement equation in the woods, US represents owners and supervisors. The role of the supervisor as a leader is just as important as understanding the behavior of the crewmembers. How do they lead? Where do their leadership skills come from? The answer to these questions can lead to an understanding of how to lead more effectively in order to help crew members reach their maximum potential.

The ability to rise above the traditions and attitudes of working in the woods, and objectively view the equation to work it for maximum employee engagement is the secret. Attitudes can be changed, so that a good leader can be admired for his attention to the soft skills of management.

Crew

Leaders need to learn about themselves and how they can improve, but they also need to understand the crew members and why they do what they do. Human nature is always predictable. By analyzing Maslow's Hierarchy of Needs in relation to crew members, and what motivates individuals, can be an eye opening exercise for managers. Through this, leaders can understand how to meet the needs of the employees on an individual level to help them work through the tiers of motivation, and to know that yes, there are ways to broaden and put emphasis on dragging trees to the landing every day, or processing products to send to the mill. (Maslow 1943)

Understanding the Crew can open new avenues for motivation and strengthened communication. Emphasizing the importance of on the spot coaching, timely reviews with opportunities for improvement, problem solving, goal setting, and genuine recognition, just to name a few.

HURDLES

The science of the biology of leadership is ever evolving, but the principles will remain the same. In an article, Social Intelligence and the Biology of Leadership, by Daniel Goleman and Richard Boyatzis in the September 2008 issue of Harvard Business Review, they discuss the research in the emerging field of social neuroscience. In this new trend of study it's revealed exactly what the brain does while people interact. This sheds light on what it takes to make a good leader. (Goleman & Boyatzis 2008) Companies on the cutting edge are taking these things into account when promoting and selecting new leaders. Attitude and people skills are more important in leading than knowledge of business management. Here is where our industry hits a hurdle, logging companies cannot go out to find crew supervisors in the mainstream who have the qualities of a great leader and stick him or her in a crane on the landing. The logging company can benefit at this point by requiring leadership training before the supervisor steps into the new position, this would give an advantage to the manager, the crew and the company.

The fact that logging is in a lot of cases is familial can lead to a separate set of hurdles. When it is a family owned business, the traditions can span generation after generation with no evidence of attention to employee engagement. In larger companies where there is a combination of family as well as regular employees, how do managers, who may be working with relatives, stay focused on the skills they need to get the most out of their people? By making this kind of training available to crew supervisors, they can keep up with trends in leadership and employee engagement that can give them the skills to handle these unique situations.

Packaging

Here is a very crucial part, the soft skills of management need to be roughed up for the delivery The biggest hurdle is to train employees in the things they have chosen to avoid by going to the woods in the first place. One logger told me "there's NOTHING soft about logging". On the contrary, there has to be soft in logging to strengthen the forest products chain. The soft skills of management will always be perceived as "touchy feely". That is exactly why, in order to get loggers to test the water, we need to label it in a way that focuses on solutions for actual issues on the job. One example, my workshop "How to Build a Kick@#$ Crew" focuses on strengthening leadership skills in order to improve production. The language of production is understood across all professions. Strengthening the bottom line will catch any logger's attention. Process improvement programs recognize the need for strengthening human relation skills as a key component for their success. There are no two ways around it; you cannot strengthen the process without strengthening the people.

Delivery

Loggers, on the average, will not be receptive to someone who has not worked in the woods and understands their stresses to the fullest extent. Why should they? How can someone offer solutions without a complete understanding of what a work day truly entails? It's impossible to inject a corporate trainer or coach with the knowledge and essence of life in the woods, it has to be lived. A few days hanging around a logging crew will not suffice. I believe we should train existing leaders from the logging industry who know the unique struggles of life in the woods. This lends credibility and empathy. Loggers are less apt to take advice from someone who has never walked in their shoes. While conducting a recent workshop, a logging contractor said that the guys would connect with me since I had experienced the same things they had. The secret to success in bringing these skills into the woods, is to marry these two together, experienced loggers with a desire to make the job a safer more productive place though the soft skills of management.

It is a tall order to create fertile ground in the woods for employee engagement in order to lay down the roots to infuse it into the culture to make it the norm. Any initiative needs to start somewhere, one way to start is to make it part of the things that loggers like. Equipment shows, organizational meetings, make it present in the standards set by organizations offering harvest and individual certification, as well as articles in trade magazines. This only scratches the surface; these principles need to be infused into the day, over and over. Workshops can start the ball rolling with an educational overview for broader understanding; successful change happens though reinforcing behavior day in and day out, over and over again.

How do we get this training to loggers who work from sun up to sundown? Bring it to the job? Create a leadership program that can be implemented at a tailgate, or an executive coach in the woods. One possible way is leadership mentors. Executive coaches are a mainstay in the corporate world, some companies budget them in for executives whether they want them or not. The reason that this is done is not because the coach has greater business acumen than a newly promoted executive, but they have the ability to be objective, and to stand back and coach based on leadership principles. This hurdle can be overcome with dedicated individuals from the woods who want to strengthen the forest products chain through the soft skills of management.

CONCLUSION

In logging we are faced with a dwindling labor pool. Professor Egan's study uncovered the lack of professionalism as one of the main reasons that parents deter kids from entering the profession of logging in Maine. (Egan 2007) A logging company's most important asset is the people who lead their people. We need to infuse professionalism into the woods by making this training available to those companies that want to partake. We need to offer training that takes into account the unique life that our loggers live in the woods. Creating leaders that understand their main job is to get the most out of each and every employee. Yes, sometimes that means you have to be a babysitter, and yes sometimes that means you have to hold someone's hand. NO, you cannot coach everyone to success, but everyone deserves the chance to be coached to success. Turnover is costly, and the one of the main reasons employees leave their job is because of their immediate supervisor, it's not usually the company they work for.

We need to sit up and take notice of the job we have before us. Not just the job of purifying the path of the wood, but the job of making this type of training readily available to the men and women who have chosen to work close to the land, who love the smell of wood and who would rather eat lunch on a stump than a fine dining establishment. We have turned away from those things to work near nature, but we need to know that we are valued enough to be strengthened, just as much as the product we move. The people side of timber harvesting needs strengthening in order to keep the wood moving in a timely and safe fashion. We need to protect and nurture our most important asset, our leaders in the forest.

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PREPARING FOR A FOREST BIOMASS INDUSTRY IN NEWFOUNDLAND AND LABRADOR

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ABSTRACT

Newfoundland and Labrador forests are generally made up of small trees and have low yields (35-120m³/ha). There is currently no commercial forest industry in Labrador and, in Newfoundland, the forest industry has been significantly downsized in recent years as a result of two pulp and paper mill closures. There is one pulp and paper mill still operating in Newfoundland and eight large sawmills are responsible for the majority of lumber produced in the province.

The closure of the two pulp and paper mills resulted in the loss of a significant market for small diameter trees. Small diameter trees were used to offset sawlog harvesting costs and, as a result, sawmills have had to close or adapt. Upgrades to increase sawmill efficiency and the utilization to unconventional forest products (ie: forest biomass) has helped the forest industry survive.

A number of challenges arise from an industry shift towards the utilization of forest biomass. Industry must adapt harvesting, transportation, handling and processing operations and also enter into new markets. Government, who own approximately 95% of forest land in the Province, must adapt management practices to reflect a changing industry. Government will assist industry with the introduction of new technology and techniques associated with utilizing forest biomass. As well, Government is addressing related issues associated with forest management including harvesting regulations, inventory estimates and tracking, volume allocations and social implications.

Keywords: Biomass, Guidelines, Harvesting, Administration

INTRODUCTION

Geographic Location and Forests of Newfoundland and Labrador

Newfoundland and Labrador (NL), the eastern-most Canadian province, is made up an island (Newfoundland) and a section of the Canadian mainland east of Quebec (Labrador). Newfoundland and Labrador cover 11 million and 29 million hectares, respectively, for a total of approximately 40 million hectares in land base (Figure 1).

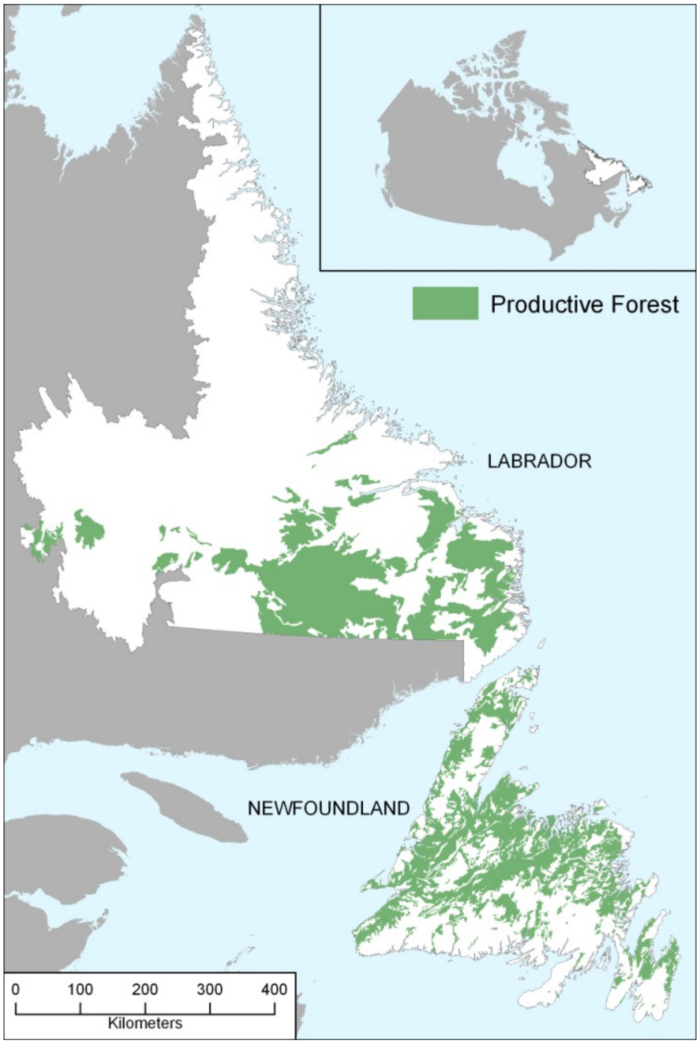
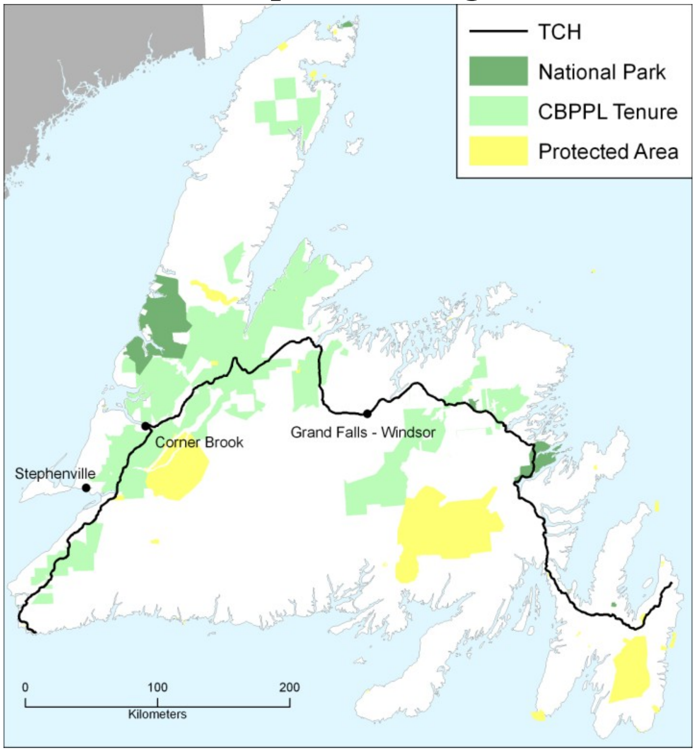


Figure 1: Productive forests of Newfoundland and Labrador

The forests of Newfoundland and Labrador form the most eastern part of the Boreal Forest Region of North America. The forests are made up of relatively small trees, primarily coniferous intermixed with hardwoods. Species variety is limited. Black Spruce (*Picea mariana*) forms about two-thirds of forests in Labrador and one-third in Newfoundland while the remaining forests are dominated by Balsam Fir (*Abies balsamea*). Limited amounts of hardwood and mixed-wood stands exist throughout the province and, where they exist, are dominated by White Birch (*Betula papyrifera*) and Trembeling Aspen (*Populus tremuloides*).

Soils in Newfoundland and Labrador are generally shallow and rocky. As a result of the cool, moist climate nutrient cycling is slow producing few highly productive forests in the province. Productive forest yields generally range from $35m^3/ha$ to $120m^3/ha$. However, commercial operations are generally not carried out in stands of less than $60m^3/ha$.

Forest Ownership and Management



Approximately 95% of the 5.6 million hectares of forest land in Newfoundland is owned by the Crown. There is one large, long-term, tenure holder in Newfoundland and Labrador – Corner Brook Pulp and Paper Ltd. (CBPPL) – who manage approximately 1.6 million hectares of forest land on the Island (Figure 2).

There are approximately 5.4 million hectares of forest land in Labrador. Of which, approximately one million hectares (18%) are productive.

Figure 2: Land ownership and management

Forest Industry

Currently, commercial harvesting is limited to Newfoundland where approximately 1.3 million hectares, or 23% of forest land on the Island (11% of Island land base), is productive and operationally available for harvest.

Newfoundland and Labrador's forest industry is undergoing a significant transformation as the historic pulp and paper industry declines in favor of a solid wood products industry and an emerging wood energy sector. A significant volume of domestic fuel wood (firewood) consumption and a small component of value-added wood products, including cabinet doors and flooring, top off the forest products industry in NL.

Newfoundland and Labrador's sawmill industry consists of over 500 sawmills which also include a number of domestic mills. Eight large sawmills account for 80-90% of the approximately 90 million FBM produced annually.

The forest industry peaked from the late 1900s to the early 2000s when there were three pulp and paper mills operating in Newfoundland. However, two of these mills closed in 2005 and 2009 (located in Stephenville and Grand Falls-Windsor, respectively) and the remaining mill , CBPPL, idled two of its four paper machines in 2007 and 2009. To remain competitive and to reduce fiber costs, CBPPL has eliminated fiber purchases from the furthest reaches of the Province; namely the Northern Peninsula, Labrador and parts of central Newfoundland.

Due to a decline in provincial markets for pulpwood, the sawmill industry has had to curtail production (as is the case for Labrador) or to seek an alternate use for small diameter wood. Some sawmills have promoted higher efficiencies with the introduction of new equipment and technology. For example, Sexton Lumber Ltd., the highest producing sawmill in the province, underwent significant mill improvements in 2009-2010 to increase efficiency. Two additional mills plan to undergo upgrades in the near future. Holson Forest Products, located on the Great Northern Peninsula of Newfoundland, has taken the path towards the production of premium wood pellets produced from sawmill residue and currently un-marketable trees (small diameter trees, off-species, and dead trees) while sustaining the harvest of sawlogs to supply their sawmill. Over the past few years, CBPPL has been harvesting forest biomass to produce heat and electricity at their mill to offset Bunker C oil requirements.

Fiber Supply

Fiber supply was stretched during the early 2000s when three pulp and paper mills operated in Newfoundland. At that time the annual allowable cut (AAC) was approximately 2.4 million m^3. However, the actual volume of wood fiber harvested in 2009 and 2010 was in the order of 1 million m^3. There is currently a surplus of fiber resource available and, if not utilized by the forest industry, these productive forests run the risk of being allocated to other interests such as wildlife, mines and energy, and protected areas (reserves and cottage development areas).

A CHANGING INDUSTRY – FOREST BIOMASS CHALLENGES

Worldwide forest product markets are changing (decline in pulp and paper sector and growth of bioenergy sector). NL’s forest industry is adapting by beginning to utilize small diameter trees (pulpwood and smaller) and previously un-merchantable trees (off-species, dead trees) for the production of energy and energy producing products. A number of challenges including administrative and management issues, for Government, and operational challenges, within the industry, will need to be addressed as the Province’s forest industry adapts.

Harvesting Guidelines

Mechanical harvesting systems were introduced in the province in the early 1980s. Whole-tree harvesting systems (feller buncher, grapple skidder and slasher at roadside) were evaluated for a number of years but environmental concerns (nutrient removals and ground disturbance) resulted in the adaptation of cut-to-length harvesting systems (harvesters and short-wood forwarders) which is currently the standard mechanical harvesting system in the province. Whole-tree harvesting is not practiced in NL.

Significant focus is being placed on developing forest biomass harvesting guidelines to minimize the effects of harvesting previously unmarketable materials from our forests. Government is working with industry to develop guidelines aimed at sustaining forests, minimizing environmental impacts and encouraging forest biomass industry development. A major environmental concern with forest biomass harvesting is nutrient depletion. There has been minimal research related to soil productivity of NL forests and the majority of NL forests are classified as low to medium capability. For these reasons, Government and industry intend to take a conservative approach to biomass harvesting and, in keeping with current practices, avoid the removal of branches and foliage from forests during commercial biomass harvesting operations. Exceptions may be made in specific situations or circumstances such as the clearing of right-of-ways or harvesting diseased or infested forest stands. In addition to sustaining nutrient levels, retaining harvesting slash on-site will provide brush mats to help alleviate ground disturbance by machinery.

Inventory and Allocation of Forest Biomass

The development and sustainability of a forest biomass industry will require close estimations of available forest biomass volumes for planning purposes. Some preliminary work has been done to estimate available forest biomass volumes within the context of current forest inventories but more research is required.

Allocation of available forest biomass is another challenge that Government will need to address. Commercial cutting permits (pulpwood and sawlogs) are distributed annually to long-term permit holders – a process that is generally not open to new entrants. It is unclear, at this time, whether or not forest biomass will be made available through traditional fiber allocations or if new allocations will be created. Government has requested forest industry development proposals for the Goose Bay area (Labrador) and central Newfoundland to consume surplus fiber in these regions. At this time, no projects have been approved but it is likely that whatever projects go ahead will include forest biomass harvesting and processing components.

Social Implications

The most prominent social implication related to forest biomass harvesting is the issue of domestic fuel wood (firewood) that is salvaged from traditional harvesting operations. The utilization of small diameter, dead and downed trees as well as off-species (ie: hardwoods) will remove fiber that would previously have been salvaged for firewood. One management option may be to avoid forest biomass harvesting in areas that traditionally have a high demand for firewood salvage.

Operational Challenges (harvesting, transportation and handling)

Operational challenges will also be encountered within the industry. Because current harvesting practices are based on a cut-to-length system a significant proportion of forest biomass is available in the currently un-utilized tree tops and butt-junks (portions of the stem, just above the stump, that are discarded due to rot or flare). Government will work with industry to evaluate new equipment and modifications to current operations to efficiently harvest, transport and handle biomass. Some options may include examining equipment add-ons such as accumulator attachments which allow multi-stem harvesting of small-diameter trees while still using existing harvesting heads. Forwarding tree-length timber rather than short-wood is another opportunity to explore. There may also be potential for in-forest or roadside chipping operations to maximize payload when trucking forest biomass out of the woods. The rate and degree of forest biomass industry development will greatly influence the rate at which new technology and equipment is adapted.

DISCUSSION

World markets for forest products are changing and the forest industry in NL and other jurisdictions is adapting. In NL, a recent move towards non-traditional forest products (ie: wood pellets) is occurring and Government and industry are faced with a number of challenges.

NL has a unique forest industry that is based on a limited fiber yield. We can observe forest biomass industries in other jurisdictions and utilize information and adapt technology, where appropriate. However, NL's forest industry will always be unique and we will have to be innovative in order to survive.

One thing is clear; the forest industry in Newfoundland and Labrador is changing. Industry and Government will have to adapt.

THE HUMAN ELEMENT IN THE FOREST VALUE CHAIN: NECESSARY CONDITIONS

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ABSTRACT

The concept of a "chain" has been used to describe relationships with those who sell timber, harvest, transport, manufacture, market and use forest products. The analogy has merit in that the "chain" is only as strong as its weakest link. Furthermore, when value is lost early in the chain, it cannot be recovered later in the process. However, some analysts and managers view a value chain or supply chain as reducible to abstractions, organizations, or budgets, company goals and contracts. In reality, the forest value chain is a more complex network of human relationships. These relationships only function well if some necessary conditions are met.

Key conditions include:

- Equity of costs and benefits
- Appropriate use of the power relationship
- The process of aligning mutual goals over time
- Security, safety, health, training, and working conditions of those in the system
- Effective feedback and communications

Examples of successes and failures for these necessary conditions are provided for discussion. Human engineering within the forest value chain is essential to its function.

INTRODUCTION

How the forestry sector worldwide came to use the paradigm of a "chain" to describe the supply of wood, the stream of values coming from the forest, or the transportation system at work is somewhat murky in its origins. The sector readily adopts concepts and terminology from other businesses and academic interests. The analogy has merit in that the "chain" is only as strong as its weakest link. Furthermore, when value is lost early in the chain, it cannot be recovered later in the process.

Relationships with those who sell timber, harvest, transport, manufacture, market and use forest products are at times linear and sequential implying a chain type of structure. However, some analysts and managers view a value chain or supply chain as reducible to abstractions, organizations, or budgets, company goals and contracts. In reality, the forest value chain is a more complex "network of human relationships."

These relationships only function well if some necessary conditions are met. Key conditions include:

- Equity of costs and benefits
- Appropriate use of the power relationship
- The process of aligning mutual goals over time
- Security, safety, health, training, and working conditions of those in the system
- Effective feedback and communications

Human engineering within the forest value chain is essential to its function.

HUMANS IN THE VALUE NETWORK

The value chain may have static relationships during periods of stability but "change" is the normal circumstance for the sector. We are seeking new innovations and improvements to operations from virtually any source. When improvement trials are undertaken and new technologies identified, the concept of a "chain" is less applicable and the following necessary conditions are needed to assure success of the improvements.

Equity of costs and benefits

The question of equity in business relationships is more than delineating who benefits and who pays. The supply chain is thought to be more flexible than what terms are specified in detailed contracts between parties. For example, preferred supplier and like relationships are used as a business basis for exchanges. However, issues of equity are rooted in the Aristotlean concepts of Truthfulness and Fairness imbedded in the contract law of most countries. When parties in the value chain reach written, oral or implied contracts, truth (disclosure) is the basis for the contract:

> *«Persons dealing at arms length with complete strangers normally do not expect those other parties to provide full information voluntarily. We expect to ask questions, to make inspections, to demand verifications».* (Cameron, p.166)

And furthermore, parties non-disclosure of vital information can be considered as contract fraud if such "essential" information would have caused the contract not to have been made.

Parties in a value chain need to be mindful of the equity in value for the exchanges that occur with their relationships and the enforceability of agreements. For example, a promise of future work as inducement for equipment purchase, business expansion, or some specific action may not be enforceable unless specified in binding written terms.

> *«Generally, one party's moral obligation to do something is not treated as legally sufficient consideration for her promise to do it ».* (Cameron, p. 165)

So many of the business relationships in the forestry subculture are done by a handshake and the good will between colleagues. However, the fundamental remedies are based both in ethical equity considerations and what the courts and her judges and juries will uphold.

Appropriate use of the power relationship

The structure of many forestry markets for services is an asymmetric one where there are many sellers and few buyers of forest operations services. The potential and the actual circumstances exist where the large buyer can use the power relationship to coerce suppliers into agreements not in their best interests. In a recession, price levels are set to cover only variable costs (labor and fuel) by some suppliers as a means of staying in business; thus, setting an unsustainable level for all suppliers.

What is the moral basis for a large organization to demand such concessions on the part of less powerful parties? The legal basis rejects the right of the larger to take advantage of the weaker.

> *«A major premise of our free, democratic society is the decision-making capacity of the individual citizen. Likewise, our free enterprise system is based on the Contract rather than Status—freely made relationships, rather than inherited group membership».* (Cameron, p. 163)

Another view of the power issue is related to the linear chain concept where managing entities adopt the "stockholder" view --that all legal means that benefit shareholders should be employed. This is in contrast with the web or network view of stakeholders where a larger number of interests combine or compete for the managers' attention and balancing of interests.(DeBrin)

The process of aligning mutual goals over time

In a chain analogy, each party in the chain need only deal with the goals given them in the downstream direction and those they give to parties they hire or contract with for services. The reality of a web structure for a value chain opens the door for influences coming from all directions to each party. What that means for small contractors is that their management requirements expand beyond what may be practical for small firms. Contractor owners and managers have a full portfolio of concerns just to keep their firms afloat in difficult times. Add to the mix that such goals may be in conflict and small firms must reconcile, balance, or ignore such demands and you realize the stress for these managers.

Contractors that have a goal of expansion or replacing capital equipment find themselves in the sights of corporate accountants who seek least cost producers. Similarly, contractors who need a given amount of production to cover costs can be at the mercy of purchasers using quotas to keep all contractors producing at subsistence levels. Finally, most contractors cannot easily predict and budget for the requirements needed to meet all environmental costs/demands or the announcement that their site will be the one chosen for the certification audit. If the contractor wants to continue working, they will need to adopt certain goals imposed by those of the value network.

Security, safety, health, training, and working conditions of those in the system

The improvements in the value chain or network have largely come from transportation and logistical efforts (Audy, et al). The network improvement computer-based models suit the geographic circumstances of forest operations and transportation. Similar comprehensive approaches have not addressed the security, safety, health, training, and working conditions of those in the system. Notable efforts on the workforce have been reported in Quebec (Lebel), Maine (Eagan), and with shift work in the South (Mitchell). A major effort for the Idaho Timber Workforce brought forward many issues and potential improvements needed that either support or hinder efforts to improve the value network (Garland). More research is needed to model and track human circumstances in the value network.

Rather than delegate human resources management to the sole domain of the individual firm, larger perspectives are needed on worker status if improvements to the value network are to be realized. For example in some regions, shortages of machine operators or the aging truck driver population potentially limit overall improvements by such measures as computer-based activity scheduling.

Effective feedback and communications

Depending on the nation, province or state, feedback and communications may be hampered by legal issues. The "arms-length" relationship needed to maintain independent contractor status between mills and entrepreneurs tends to limit direct communications between stakeholders in the value network. In fact, the collection of contractors in a single location raises legal issues of collusion whenever prices (and other competitive issues) are discussed. Mills are concerned that contractors are not considered "employees" for tax purposes, workers compensation or liability issues. What is disturbing for some of these limitations is that simply the allegation of impropriety becomes an onerous process to defend against the charges.

Despite such concerns, when contractors are able to talk freely, they provide insights that would be useful to many stakeholders in the value network, including corporate managers, accountants, environmental staff, marketing folks, and stockholders. From the mill perspective, their source of information most often comes directly from procurement staff who may have vested interests relative to their own position representing the firm. Certainly more efforts with anonymous surveys, forums, and communications might help identify human issues important to the value network.

INNOVATION AND CHANGE IN THE VALUE NETWORK

To examine human issues in the value network, a review of a particular innovation is useful. A description of the process of developing the new technology is followed by a series of questions related to the human interactions to consider. The scenario takes place on the Olympic Peninsula of Washington state.

The Opportunity

Slash piled by machine after logging has value for energy at co-generation facilities and it costs money and delays to burn piles.

The Issues

- Slash must be densified by grinding to fill viable load weight
- Widely dispersed logging units containing slash piles
- Road system unsuitable for standard tractors and chip vans: grades, alignment, surface, other limits, eg environmental.
- Cost of feeding, grinding, and transporting energy wood with low margins limits area of operations: NO SUBSIDIES AVAILABLE
- Multiple landowners have slash piles to burn in excess of energy wood demand

Potential Solutions

- Cherry-pick the closest, suitable piles with available technology and let rest go begging
- Modify the roads for existing technology with grading, re-surfacing (with wood chips?), and get to largest concentrations of piles
- Devise new technology to address the problems

The Approach

Hermann Brothers elects to first try road modifications using their existing technologies of standard tractors, chip vans, grinding operation to work with landowners. While successful for some areas, opportunities are lost if the grinding operations cannot access any location that a log truck had accessed.

New technology was needed and the first approach called for six-wheel drive tractors to access the road system. Road modifications were still needed for standard chip vans. However, Europeans have used radio-steered trailers on some forest operations. Could a chip van be radio-steered? Hermann Brothers engages Western Trailer to help develop a force steer biomass chip trailer with two steered axles on the rear of the trailer (Taylor).

The Solution

The combination of six-wheel drive tractors and force steered biomass trailers is successful after several trials and modifications. How then does Hermann Brothers implement the improved system considering the human elements in the value network? (Hermann)

Humans in the Value Network: the Questions

Considering the number of interactions in a value network, a selected number of questions are posed for the process of implementing the innovations of Hermann Brothers. The necessary conditions described earlier are imbedded in the questions. Example questions represent what human concerns need to be addressed and are only for illustration.

- Will drivers adapt to force steer trailer controls?
- Can drivers implement computer-based steering control maintenance?
- Will landowners accept use of technology on existing roads?
- Who will pay development costs for the new trailers?
- Who pays for costs of trial-and-error of the prototypes?

- Will forest managers realize the cost benefits of reduced burning and pass them to pile utilization costs?
- Will wood energy purchasers compensate for the additional availability of wood supply?
- Who will finance a 3 million dollar grinding/transport operation?
- Who will organize the supply of chip piles for the logging companies?
- Will trailer manufacturer produce viable product for wider sales to recoup development costs?

CONCLUSION

Successful responses to the questions above determine whether the innovation will be adopted and sustained. The value chain concept is in reality a value network of humans. Their issues are critical to forestry sector improvements.

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CHIP PROPERTIES FROM OPERATIONAL HARVESTS OF PINE STANDS IN THE SOUTHERN US

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ABSTRACT

A thorough body of literature exists to describe the characteristics of tree components (wood, bark, and foliage) for use in bioenergy production. Relatively little information is available, however on the characteristics of wood biomass feedstocks gathered directly from the forest. We designed a controlled experiment to assess the characteristics of operationally harvested wood chips across a variety of stand ages, species, and soil types in the coastal plain of Georgia. A whole tree chipping crew harvested ten stands, five loblolly pine (*Pinus taeda*) and five slash pine (*P. elliotti*), in the coastal plain of Georgia. Five samples of chips were taken from each tract during harvesting from trees dispersed across the sites. Size classification and bark, foliage, and moisture content were assessed, as well as full nutrient content analyses and both energy and ash content. Site and stand factors impacted moisture content of samples, as well as operational factors such as time between felling and chipping.

INTRODUCTION

The rapid development of wood-based bioenergy markets in the southern United States has created a need for detailed understanding of the properties of the forest resources readily available for bioenergy production. Many lab-based analyses on the properties of wood, bark, and foliage have been performed to determine the characteristics of both hardwood and softwood fuels. Howard (1973) showed that pine needles typically produce more energy per pound than does pine bark while bark has slightly higher energy per pound than wood.

While this information is extremely useful to understanding the energy characteristics of the resource, biomass delivered to consumption facilities can be a combination of all three components of the tree in addition to any possible contaminants that may be introduced during the harvesting process. Extensive, field-based sampling is needed to assess the range of possible feedstock characteristics and successfully match feedstocks to potential markets. A careful analysis will ideally identify correlations between site, stand, and operating conditions and both desirable and undesirable feedstock properties.

This report details an extensive analysis of wood samples collected over five weeks from a whole-tree chipping crew operating across a range of timber stand types in southeastern Georgia. This analysis will further improve the level of knowledge regarding the characteristics of woody biomass produced by in-woods chipping.

METHODS

Ten tracts were selected from the Coastal Plain of Georgia. Tract acreage ranged from 5.5 to 42.2 acres, with ages ranging from 8 to 17 years. Five tracts were loblolly pine (*Pinus taeda*) plantations and five were slash pine (*P. elliotti*) plantations. On each tract, five plots were established covering the range of topography and soil types represented. Twenty-five trees were marked for removal in each plot. A different color of paint was used on each plot within a tract to differentiate them. A subset of painted trees was measured for diameter and height.

Each tract was thinned by a logging operation using one feller-buncher and two grapple skidders. Stems were fed into a Morbark 30/36 drum-style chipper. In each painted plot, all marked stems were felled and placed into a single bunch for extraction by the skidder. As each painted bunch was brought to the landing and fed to the chipper, we sampled the chips using a chip sampling tube placed near the throat of the chipper. At roughly 20-second intervals during the chipping of the painted trees, we placed the sampling tube into the stream of chips for 5-10 seconds to collect a sample of roughly twenty gallons. All painted trees were fed to the chipper with the limbs intact. This sample was thoroughly mixed, and three subsamples of approximately 2 kg each were placed in heavy-duty paper bags. Each bag was immediately placed on a scale and exact weight was recorded. Temperature and humidity at the time of sampling was recorded, as well as the duration of time between the felling of stems and their chipping.

Two of the sample bags were placed in a 105 degree C oven for 24 hours drying. Oven-dry weight and moisture content were recorded. One of the sample bags was kept intact as a backup, while the other was processed in a hammermill through 1mm screens and sent to the University of Georgia Soil, Plant and Water Analysis Lab for total mineral analysis as well as combustion in a bomb calorimeter to determine energy and ash content. The third sample bag was sorted in a chip classifier to determine the size distribution of the chips. Samples were sorted into seven size classifications: <3 mm, 3-5 mm, 5-7 mm, 7-15 mm, 15-45 mm, 45-63 mm and >63mm. Foliage and bark content were also recorded with foliage removed from the full sample, and bark weighed separately from wood down to 7 mm. Inner and outer bark were not differentiated. For the purposes of this report, chips sized 15-63 mm were deemed acceptable or "Accept", >63mm were oversized or "Overs", 7-15mm were considered undersized "Under", 3-7 mm were considered "Fines", and <3mm "Dust". It should be noted that adjustments to the chipper anvil and sharpened angle of the knives were not made, which could have a substantial impact on the size distribution.

We examined the chip properties to determine if any significant differences occurred between the samples. Samples were collected from trees growing in seven different soil types; however, many of the soils were only represented by a small number of samples. To draw meaningful comparisons between properties of wood chips from different soils, statistical tests were performed on characteristics of the soils, such as texture, drainage class, and site quality, as determined by the soil classification. Energy, ash, and moisture content were regressed against site and stand parameters to determine which conditions were influential in determining feedstock properties. Stand and harvest conditions were also examined to determine if they were useful in predicting the size distribution of chips produced.

RESULTS

Moisture content did not vary significantly between species (Table 1). A regression of moisture content against recorded stand and site parameters yielded the following equation:

MC (%) = 64.08 – 0.177 * SI – 0.571 * Age + 0.075 * Temp

$R^2 = 0.478$

$P < 0.001$

SI = Site Index for loblolly pine, base age 25, feet

Age = Current age of the stand, years

Temp = Ambient air temperature at time of sampling, degrees F

The equation suggests that younger stems have higher moisture content and faster growing stems (higher site index) have lower moisture content. It also shows a very weak positive relationship between the temperature at the time of sampling and the moisture content of chips. As none of the stems processed were on the ground for more than four days prior to chipping, the expected result of higher temperatures driving moisture content lower was not observed.

Moisture content tended to have a weak but significant positive correlation with most of the chemical properties tested. Exceptions were energy, carbon, manganese, sodium, and silicon levels. Foliage content also correlated with moisture content, which may explain some of the nutrient level impacts, as foliage correlated with many of the nutrient levels tested.

Table 1: Chip properties compared between loblolly and slash pine (n = 50).

Wood Chip Characteristic	Loblolly	Slash	*P* - value
Moisture Content (% wet basis)	51.8	50.5	*0.122*
Energy Content (BTU/lb)	8304	8394	*0.031*
Ash Content (%)	0.53	0.46	*0.222*
Accepts (% 63-15 mm)	48.5	44.4	*0.031*
Foliage Content (% of wet weight)	1.2	1.3	*0.725*
Bark Content (% of wet weight)	10.5	14.8	*0.001*
Carbon (%)	48.0	47.8	*0.687*
Nitrogen (%)	0.10	0.09	*0.352*
Phosphorous (ppm)	113.3	110.1	*0.792*
Potassium (ppm)	423.8	403.9	*0.599*
Silicon (ppm)	174.2	58.9	*0.001*

Energy and Ash Content

Energy content of chips ranged from 7866 to 8656 BTU/lb. A small but significant difference in average energy values was seen between loblolly pine and slash pine (Table 1). The higher heating values (HHV) calculated for chip samples are slightly lower than many reported values for wood, bark, and needles of southern pines individually, but are consistent with reported averages for pine limbs and tops (Howard 1973). Wang et al. (1982) reported average energy content around 8500 BTU/lb for slash pine stem and bark wood in northern Florida. Two samples produced HHV below 7900 BTU/lb, while all other samples were above 8050 BTU/lb.

Ash content of samples varied between 0.24% and 1.32% of dry weight. Ash did not vary between species (Table 1). Ash levels correlate with age of the stand (Figure 1), but did not correlate with foliage content (Figure 2) or bark content.

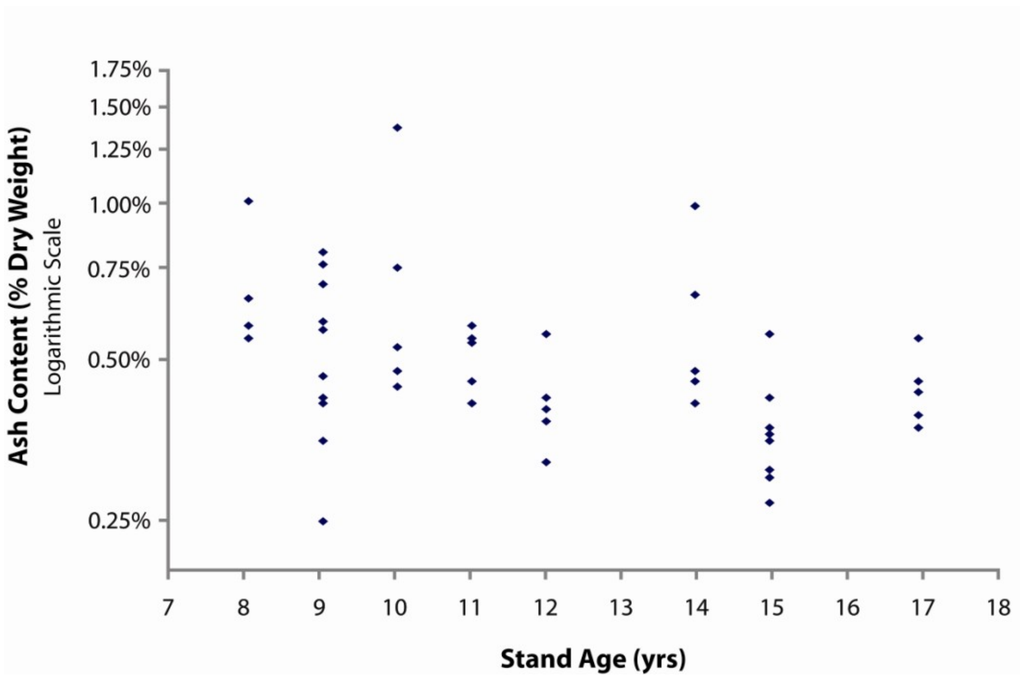

Figure 1: Relationship between stand age and ash content of chips as a percent of the dry weight. Ash content is represented on a logarithmic scale to more clearly represent the differences at lower values.

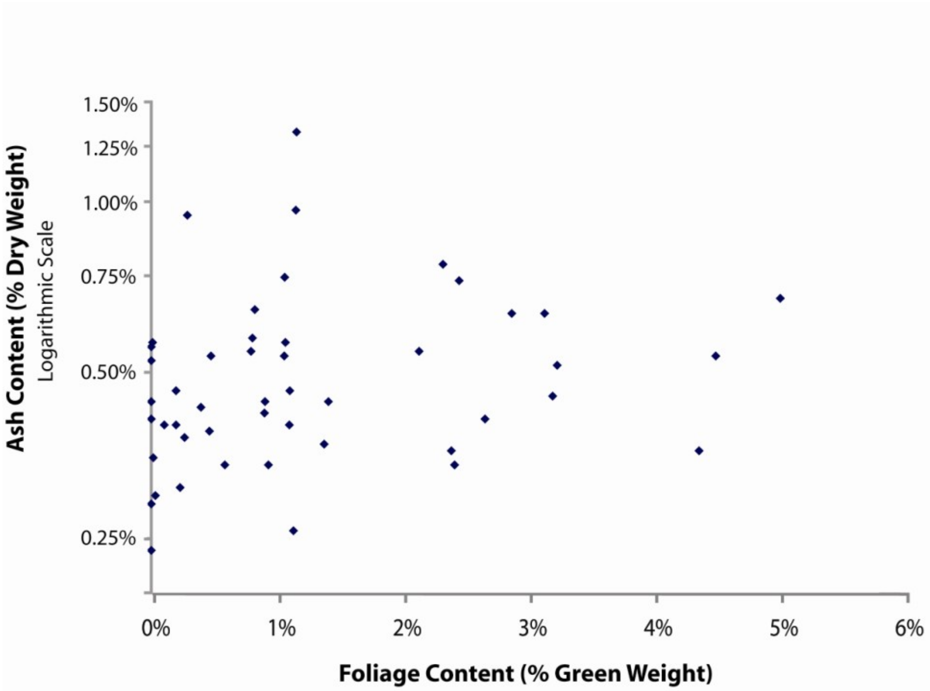

Figure 2: Relationship between measured foliage content and ash content of chips as a percent of the dry weight. Ash content is represented on a logarithmic scale to more clearly represent the differences at lower values.

Soil Properties

A number of chip properties appear tied to soil properties. Energy content differed between soil drainage classes, with "poorly drained" soils representing the highest energy levels. Examining closer, slash pine samples taken from poorly drained soils produced the highest HHV, while loblolly pine samples taken from similar sites were among the lowest. Site quality as indicated by soil type did not correspond in any meaningful way with energy content, nor did soil texture indicators; though both were correlated with moisture content of wood chips. Samples taken from spodic soils had higher average moisture contents than other soils, but it should be noted that only one site had soils of this type, corresponding to the youngest stand of trees sampled. Nutrient levels in the chip samples were often correlated to soil properties. Potassium levels tended to increase with increasing site quality or decreasing soil drainage class. Carbon and nitrogen levels were significantly different between differing site quality and drainage classes, but did not exhibit any consistent patterns. Ash and silicon levels in the chips were independent of any tested soil properties.

Size Distribution

Chips sized 63-15 mm averaged 48% of the total weight of chips, with loblolly pine averaging roughly 4.6% higher accepts than slash pine (Figure 3). Slash samples had approximately 3% greater proportion of chips as fines (3-7 mm) and 1% greater as dust (<1 mm).

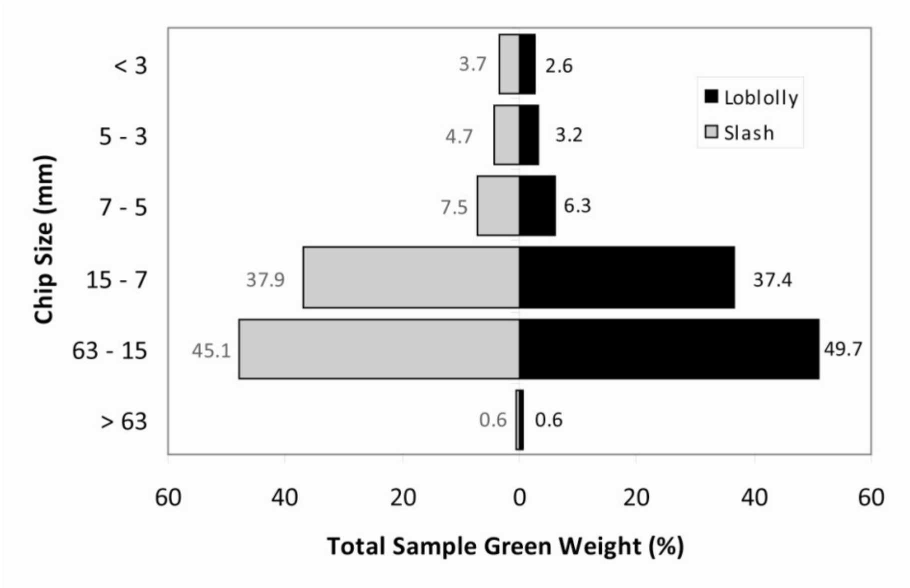

Figure 3: Size distribution of wood chips from loblolly pine and slash pine stands.

Knife wear had very little impact on chip size distribution (Figure 4). Samples chipped within the first five truckloads processed by a set of knives averaged 52% accepts, 4% greater than samples chipped by knives with greater wear. No differences in the percentage of acceptable chips were seen after five loads had been chipped on a set of knives. The majority of the shift in acceptable chips resulted in an increasing proportion of undersized chips (15-7 mm). No consistent changes were observed in smaller sized chips.

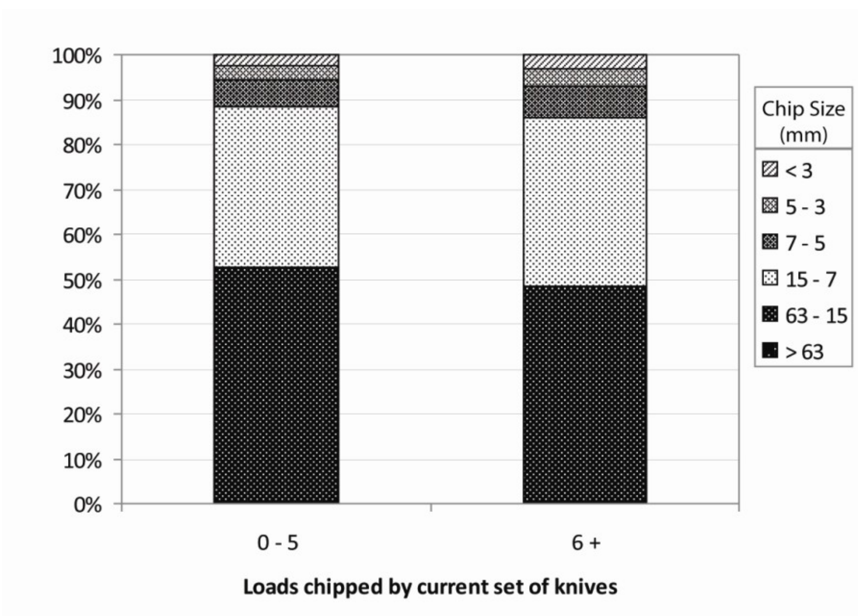

Figure 4: The impact of knife wear, as measured by the number of truckloads of chips processed prior to sampling, on the size distribution.

Foliage and bark levels were correlated with phosphorous, sulfur and nitrogen concentrations in the wood samples (Table 3). None of the correlations were particularly strong (the strongest is between bark and sulfur contents and corresponds to an r^2 of only 0.30), but they were significant despite the numerous other sources of variability in the data, such as species, age, and site differences.

Table 2: Correlation (Pearson's *R*) between foliage and bark content and chip properties. Statistically significant correlations are highlighted in bold font ($p < 0.05$).

	Foliage Content		Bark Content	
	Correlation (*R*)	*P* - Value	Correlation (*R*)	*P* - Value
Moisture Content (% wet basis)	0.319	*0.008*	0.192	*0.114*
Energy (BTU/lb)	-0.100	*0.491*	0.063	*0.666*
Ash (% dry wt)	0.182	*0.206*	0.206	*0.151*
Carbon (% dry wt)	0.082	*0.571*	0.215	*0.133*
Nitrogen (% dry wt)	0.408	*0.003*	0.338	*0.017*
Sulfur (% dry wt)	0.449	*0.001*	0.550	*< 0.001*
Aluminum (ppm)	0.148	*0.303*	0.100	*0.488*
Calcium (ppm)	0.244	*0.088*	0.223	*0.119*
Iron (ppm)	0.076	*0.599*	-0.113	*0.434*
Manganese (ppm)	0.003	*0.984*	-0.321	*0.036*
Magnesium (ppm)	0.227	*0.113*	-0.062	*0.669*
Phosphorous (ppm)	0.448	*0.001*	0.394	*0.005*
Potassium (ppm)	0.116	*0.422*	0.236	*0.099*
Silicon (ppm)	0.186	*0.196*	-0.256	*0.073*
Zinc (ppm)	0.070	*0.658*	-0.101	*0.523*

DISCUSSION AND CONCLUSIONS

Moisture content of the samples agreed with previous studies showing "fresh" chips between 50 and 55% moisture. The lack of a correlation between moisture content and the amount of time between felling and chipping of stems was unexpected. Previous studies examining field drying of stems have suggested that reductions in moisture content will occur following harvest (Klepac *et al*. 2008). The trees left to dry longest in this study remained on the ground four days prior to chipping, while the quickest were chipped within an hour of felling. All of the harvests were thinnings, so most of the felled stems sat under at least partial shade as well. No difference was seen in moisture content when comparing the ten samples which had been felled longest and the ten which were chipped the quickest (p = 0.416). This implies that within a conventional harvesting operation, separating felling and skidding by as many as three or four days does not seem to offer a distinct moisture content advantage.

In general, older stands had lower ash and moisture content. Slash pine stands exhibited decreased energy content in older stands (slash pine stands ranged in age from 10 - 17 years old), while loblolly pine stands showed no pattern (age range 8 – 15 years old). There is no previous research to suggest a negative correlation between age and energy content, which implies there may be other factors causing this result for slash pine stands.

Ash content in all samples was similar to levels found in whole-tree chip samples from previously reported studies. Aman *et al*. (*in review*) found ash content of 0.6% in whole tree chips. Chips produced solely from limbs and tops of pine stems, by comparison, averaged 1.5% in previous studies (Baker 2010). The top of the tree appears to be the portion most likely to gather dirt during ground-based extraction, so when a substantial portion of the stem is included in the chipping material, a smaller percentage of the total volume will contain high ash contents.

The size distribution of chips varied from sample to sample, but was fairly stable overall. Given the knife setup on the chipper, roughly half of the weight of chips produced was within the 16 – 63 mm range. A slight adjustment on the knife arrangement could likely increase this proportion significantly. The percentage of acceptable chips only decreased 4.5% as the knives became worn, with no significant reductions after five loads had been chipped. A significantly higher proportion of loblolly pine chips were within the acceptable size range, despite no differences in the average knife wear between stands of the two species. If stringent size requirements for chips are in place, this may warrant further investigation.

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CHANGES IN FUEL QUALITY OF LOGGING RESIDUES DURING FIELD STORAGE IN NORTHWESTERN ONTARIO

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ABSTRACT

Logging residues are recognized as a low hanging fruit in regard to biomass for energy production. However, the feasibility of procurement is sensitive to moisture content, thermal value and ash content of the feedstock. Studies in Europe have demonstrated that biomass can be stored in the field to improve fuel quality.

This study was performed to investigate the effect of storage method and duration on fuel quality of logging residues. The fuel qualities assessed were moisture content (MC), thermal value and ash content. The MC was reduced from a green state to 27% after 1 year of storage and to 21.9% (dry weight basis) after 2 and 3 years of storage in roadside slash piles. In cut-to-length blocks, the MC was reduced from a green state to 30.1% after 1 year of storage and to 24.8% after 2 and 3 years of storage. Windrows displayed lower MC values than beehives and softwoods generally displayed lower MC values than hardwoods with few exceptions. The thermal values ranged from 19.5 to 23.1 $MJ\cdot kg^{-1}$; the number of storage years had no significant effect on the thermal value, but diameter and species did. Generally, smaller diameter stems displayed higher thermal value than larger diameter stems and softwoods contained higher values than hardwoods. The ash content ranged from 0.4% to 8.4%; diameter produced significantly different ash contents in logging residues of both cut-to-length blocks and roadside slash piles, with smaller stems having significantly higher ash conent. In cut-to-length blocks, the ash content was reduced significantly with an increase in the number of storage years.

In northwestern Ontario, the storage of logging residue in the field for as short as one summer period can lead to a significant reduction in moisture content and thus improvement in the fuel quality, consequently leading to an overall cost reduction of the biomass feedstock.

Keywords: Biomass; bionenergy; cut-to-length; moisture content; thermal value; ash content

INTRODUCTION

Logging residue is produced year-round, however its immediate transport is costly due to high moisture content at green state and high bulk (Gigler *et al.* 2000; Pettersson and Nordfjell 2007).

Studies in Europe have shown that logging residue can be stored in the field to improve the fuel quality (Jirjis 2005). The form, duration of storage and the weather conditions affect fuel quality (Pettersson and Nordfjell 2007). There has been no such research done on fuel quality of logging residues in northwestern Ontario. Knowledge gained in Europe is transferable to northerwestern Ontario to a certain extent, but due to the differences in stored material and weather conditions it is not completely valid.

The objective of the study is to determine how storage pile form, time, species and logging residue diameter affect fuel quality (moisture content (MC), thermal value and ash content). It was investigated whether there are statistical differences in the MC, thermal value and ash content of logging residue stored in various pile configurations for a range of durations.

METHODOLOGY

The study materials were located in harvest blocks to the west of Atikokan, Ontario, Canada. The mean annual temperature and precipitation accumulation recorded by the Atikokan weather station (AUT) (Lat. 48^0 45.667' N, Long. 91^0 37.683'W) was 2.7^{o}C and 645 mm, respectively.

Analysis of variance (ANOVA) test was carried out using the General Linear Method in SPSS to test the null hypothesis: harvest year, species, pile shape and pile height have no effect on the mean moisture content , thermal value and ash content of full tree (FT) roadside logging residue. Storage years included materials stored for 1, 2 and 3 drying seasons. The shape of the slash piles selected in the study fall either under the general category "half-section of sphere" or "half-ellipsoid" referred to as beehive and windrow, respectively (Hardy 1996). Species were divided into the general categories of softwoods and hardwoods. The heights of the piles were recorded as being either greater or less than 2 m; the width ranged from 8 m to 16 m. The experimental design of the model is a full factorial design. ANOVA was also carried to determine if storage years, species and logging residue diameter led to a significant difference in the moisture content, thermal value and ash content of logging residue in cut-to-length (CTL) blocks.

A list of blocks containing slash piles was obtained from the AbitibiBowater Inc. office in Fort Frances. This list included harvest blocks from three different Annual Work Schedules (AWS): 2006/2007, 2007/2008 and 2008/2009. Harvest blocks and piles were randomly selected from the list. Slash piles were measured for MC at various depths and in CTL blocks, a line intersect method was used to collect moisture content information using Protimeter Surveymaster Moisture Meter. Samples were brought back to the lab to determine thermal value and percentage ash content. Data was collected during June and July, 2008 and 2009. In the laboratory, a Parr 6200 Bomb Calorimeter was used to determine the thermal values of the samples collected in the field. Ash content was determined using the methodology outlined in Sluiter *et al*. (2008).

RESULTS & DISCUSSION

Moisture Content

A summary of moisture content observed in FT roadside slash piles is presented in Table 1 along with corresponding standard deviations. The average moisture content on a oven dry basis (OD) basis ranged from 14.1% to 35%. The average moisture content observed in this study is lower than values observed in the Scandinavian countries (Nurmi 1999; Lehtikangas 2001; Jirjis 2005; Petterson and Nordfjell 2007). The lower moisture content achieved in this study can be attributed to the continental climate in northwestern Ontario (Gamble 1997). Hot summers in our study area lead to feedstock drier than those presented in studies above. Comparatively, in the Nordic countries the climate is moderated due to maritime influences and thus do not reach similar extremes.

Table 1: Summary of average moisture content (OD basis) values from top 1.5 m of FT roadside slash piles.

Drying Seasons	Shape	Species	Pile Height			
			< 2 m	Standard Deviation	> 2 m	Standard Deviation
1	Windrow	Softwood	20.9	2.56	20.3	3.42
		Hardwood	26.8	3.78	29.7	7.81
	Beehive	Softwood	27.8	4.27	22.9	1.56
		Hardwood	35.0	7.77	32.4	2.00
2	Windrow	Softwood	23.6	2.28	21.5	2.72
		Hardwood	16.5	2.74	22.1	4.25
	Beehive	Softwood	14.1	1.25	16.9	4.01
		Hardwood	26.9	3.37	30.9	3.87
3	Windrow	Softwood	18.2	0.78	18.7	6.76
		Hardwood	21.8	2.90	22.6	5.19
	Beehive	Softwood	16.6	2.01	18.9	4.16
		Hardwood	29.4	14.34	31.6	5.12

A summary of moisture content observed in the cut-to-length blocks is presented in Table 2 along with the standard deviation values. Logging residue in cut-to-length blocks show a higher variation in moisture content than logging residue in FT roadside slash piles, the average moisture content ranged from 11.9% to 40.7% OD basis.

Analysis of variance indicates that storage period has a significant effect on the mean MC of FT roadside slash piles and also of logging residue spread in the cutover. Post hoc analysis of slash pile MC using Duncan test showed that, year 1 piles displayed significantly higher ($p<0.001$) MC of 27% (OD) compared to year 2 and 3 piles which displayed an average MC of 21.9% (OD). CTL blocks showed a comparable trend; logging residue from year 1 showed significantly higher ($p<0.05$) MC with MC value of 30.1 % (OD). Year 2 and year 3 had an average MC of 24.7% (OD).

Table 2: Summary of average moisture content (OD basis) values of logging residue from cut-to-length blocks.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	26.5	13.9	18.0	4.8
	Hardwood	40.7	17.8	35.1	22.2
2	Softwood	20.3	8.8	11.9	1.4
	Hardwood	35.1	19.8	28.6	17.8
3	Softwood	27.9	15.4	16.2	5.6
	Hardwood	38.0	15.2	19.8	10.2

*Large = > 4 cm in diameter
Small = ≤ 4 cm in diameter

Once cut, green wood gradually approaches an equilibrium state that fluctuates with temperature and relative humidity (Siau 1995). It is the hygroscopic nature of cell walls that allows the equilibrium moisture content to fluctuate in this manner. Our results suggests that the average MC of logging residue drops further in the second drying season, indicating that equilibrium moisture content itself decreases further. Our results are similar to the trends found by Millet (1953), Hall and Rudolph (1957) and Truman (1959) on pulpwood drying rates.

Analysis of variance reveals that species had a significant effect (p<0.001) on the mean MC value of logging residue in both FT roadside slash piles and cut-to-length blocks. In both FT roadside slash piles and CTL blocks, softwoods produced lower moisture content than hardwoods. The lower MC values displayed by softwood species is best explained by the differences in the chemical composition and anatomical construction between hardwood and softwood species. In hardwoods, hemicelluloses constitute approximately 25-40% as opposed to 20-30% in softwoods (Siau 1995). Hemicellulose is the most hygroscopic component of cell wall followed by cellulose and lignin (Christensen and Kelsey 1959). Consequently, the cell walls of hardwoods will have more potential bonding sites available for water.

An added factor that may have contributed to the lower MC values in softwoods is transpiration drying (Angus-Hankin *et al.* 1995). The stomata of the leaves and needles are the main pathways for evaporation of moisture from a living tree (Raven *et al.* 1999). It was observed that needles were intact in softwoods for longer durations than leaves on hardwoods. A similar observation was made by Simola and Makela (1976), and Rogers (1981).

FT roadside slash pile height showed no significant effect on the MC. However, since the measurement was only performed to a depth of 1.5 m, no conclusions on the material below this depth can be made. In the literature on pile heights, Jirjis (1995) and Pettersson and Nordfjell (2007) report that smaller piles lose moisture rapidly when the vapour pressure deficit of the ambient air is high in the summer. However, the reports also state that when the temperature and RH drop, smaller piles regain moisture more rapidly.

There was a significant effect (p<0.001) of pile shape on the MC of logging residue in FT roadside slash piles. In addition, the interaction between storage year, shape and species is significant (p<0.01. With regard to hardwoods, beehives display higher MC values than windrows in all storage years. Similar trends are not prevalent in FT roadside slash piles of softwoods; in storage year 1, windrow piles show lower moisture content than beehive, in year 2 beehive piles show the lower moisture content and in year 3 the values are equivalent.

The lower moisture values displayed by windrows can be attributed to the greater surface area to volume ratio compared to beehive piles. In a study conducted by Hall and Rudolph (1957) on jack pine pulpwood piles, the moisture content fluctuation was much higher in the exposed wood than the inside wood. Also, the widths of windrow piles are much smaller compared to beehive piles; smaller width translates to less resistant to airflow, leading to faster drying of the piles.

The significant interaction is most likely due to the level of compaction in the piles. Hardwood piles had a greater amount of void space compared to softwood piles. The more pronounced branching of hardwoods allows less compaction hence there is a higher percentage of void space in hardwood piles which translates to a lower airflow resistance by hardwood piles. Therefore in hardwood piles, beehives show a higher MC than windrows. However, in softwood piles, the reduced void space leads to higher airflow resistance especially in the beehive piles. Consequently, the majority of logging residue in softwood beehive piles is protected from interface with the ambient air; it takes longer period for logging residue in these piles to reach EMC but once it is achieved, the fluctuations occur at much slower rate compared to windrow piles.

Thermal Value

A summary of thermal values and the corresponding standard deviation of samples from FT roadside slash piles of both types, windrows and beehives, are presented in Table 3. The values ranged from 19.9 to 23.1 $MJ \cdot kg^{-1}$. A summary of thermal values and the corresponding standard deviation values of logging residue from cut-to-length blocks is presented in Table 4. The values ranged from 19.5 to 22.8 $MJ \cdot kg^{-1}$.

In FT roadside slash piles there was a significant difference in thermal value between species, but not in the CTL blocks. Additionally, species had an interaction effect with storage years and location in pile. Softwood constantly showed slightly higher thermal value than hardwoods with one exception; year 3 hardwoods at the surface of the piles showed higher average thermal value than softwoods but the difference was not significantly different. The highest average thermal value was displayed by softwoods from inside of the pile and the lowest value was displayed by year 2 hardwoods at the surface of the piles. The higher thermal value per kg displayed by softwoods can be attributed to the higher percentage of lignin and resin present in softwoods compared to hardwoods (Hakkila 1989; Plomion *et al.* 2001). Lignin and resins have considerably higher thermal values than cellulose and hemicellulose (GCEP 2005). However, also need to take into consideration that most hardwoods have a higher specific gravity than softwoods, and thus significantly impacts thermal value per m^3.

Table 3: Summary of average thermal values in $MJ \cdot kg^{-1}$ of logging residue from FT roadside slash piles.

Drying Seasons	Location*	Species	Diameter**			
			Small	Standard Deviation	Large	Standard Deviation
2	Inside Pile	Softwood	21.2	0.4	22.4	0.5
		Hardwood	20.3	0.6	21.7	0.8
	Surface	Softwood	21.2	1.0	22.3	0.5
		Hardwood	20.4	0.5	20.9	0.9
3	Inside Pile	Softwood	20.8	1.0	23.1	0.2
		Hardwood	20.0	0.0	21.4	0.4
	Surface	Softwood	19.9	0.2	21.7	1.2
		Hardwood	20.7	1.0	22.5	1.1

* Inside pile is logging residue samples from depth of 1.5 m

**Small = ≤ 4 cm diameter, Large = > 4 cm diameter

Table 4: Summary of average thermal values in $MJ \cdot kg^{-1}$ of logging residue from cut-to-length blocks.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	20.1	0.12	21.3	0.06
	Hardwood	20.4	0.22	21.4	0.57
2	Softwood	21.6	1.86	22.0	2.10
	Hardwood	20.2	0.83	20.8	0.45
3	Softwood	19.5	0.50	22.8	1.76
	Hardwood	20.7	0.89	22.1	0.37

*Large = > 4 cm in diameter

Small = ≤ 4 cm in diameter

Diameter led to significant difference (p<0.001) in the mean thermal value in both FT roadside slash piles and logging residue within cut-to-length blocks. Smaller diameter branches display higher thermal values than larger diameter branches in both cases. Similar results were observed by Singh and Kostecky (1986) in samples collected in Manitoba. In softwoods, the higher thermal values in smaller samples can once again be attributed to the presence of compression wood and also a higher percentage of bark. The percentage of bark increases sharply as the branch diameter decreases (Wellwood 1979; Hakkila 1989). Bark generally has a higher heat value than stem wood because it is richer in lignin, resin, terpenes and other combustable elements (Hakkila 1989). In hardwoods, although smaller branches contain lower amount of lignin due to the presence of tension wood, lignin content in hardwood bark is three to four fold compared to softwood bark (Nurmi 1993). The higher percent of lignin in bark coupled with the fact that there is a greater percentage of bark gives smaller branches the higher thermal value.

There is no significant difference in the mean thermal values of logging residue due to storage durations 1 to 3 years in FT roadside slash piles or cut-to-length logging residue. Hakkila (1989) mentions that although the heat value of logging residue changes during storage, the change is insignificant. This can be accredited to low MC which limits microbial activities thus decay of wood. Decay in wood can be initiated only at MC of over 26-32% (OD basis) (Hudson 1992).

Ash Content

A summary of ash content and the corresponding standard deviation values of logging residue from FT roadside slash piles are presented in Table 5. The values range from 2.7% to 8.4%. There was a noticeable difference in the ash content between large diameter samples and small diameter samples. A summary of ash content and the corresponding standard deviation values of logging residue from cut-to-length blocks are presented in Table 6; the values ranges from 0.4% to 4.2%.

Table 5: Summary of average ash content values of logging residue samples from FT roadside slash piles.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	3.5	0.29	3.8	0.20
	Hardwood	2.7	0.88	8.4	0.22
2	Softwood	4.9	0.63	6.1	0.59
	Hardwood	4.6	0.96	7.6	0.16

*Large = > 4 cm in diameter
Small = ≤ 4 cm in diameter

Table 6: Summary of average ash content values of logging residue samples from cut-to-length blocks.

Storage Years	Species	Diameter*			
		Large	Standard Deviation	Small	Standard Deviation
1	Softwood	2.6	1.9	3.5	0.5
	Hardwood	1.7	0.2	4.2	0.0
2	Softwood	0.7	0.6	2.1	1.2
	Hardwood	1.9	0.0	4.2	0.2
3	Softwood	0.4	0.1	1.7	1.0
	Hardwood	1.5	1.8	1.8	0.2

*Large = > 4 cm in diameter
Small = ≤ 4 cm in diameter

Once again the difference in the ash content between large diameter samples and small diameter samples is noticeable. Storage years showed no significant difference in the ash content of FT roadside slash piles, however, in CTL blocks, storage years did show a significant difference

(p<0.01) in the ash content values. The percentage ash content has a decreasing tendency with the number of storage years. Storage years 1 and 3 have values significantly different (p<0.05) from each other but neither of the year show a significant difference from year 2. Similar significance due to storage duration was not observed in FT roadside slash piles because the majority of logging residue is protected from weather factors. In CTL blocks, the majority of logging residue is exposed to environmental factors resulting in leaching of elements by rainfall (Jenkins *et al.* 1998; Vamvuka *et al.* 2008).

Diameter had a significant effect (p<0.05) on the mean ash content of logging residue from both FT roadside slash piles and CTL blocks. There was also an interaction effect between diameter and species in logging residue from FT roadside slash pile. Large diameter branches show lower ash content than small diameter branches. In large branches, softwoods show higher ash content but in small branches hardwoods show higher ash content than softwoods. In the cut-to-length blocks softwood shows lower ash content than hardwood and smaller diameter branches show significantly higher ash content (p<0.05) than larger diameter branches. Ash content is inversely proportional to the stem diameter. Majority of ash in a tree is concentrated in the bark tissues because of its importance to physiological functions (Bowyer *et al.* 2002). As discussed earlier, smaller diameter branches have much higher proportion of bark compared to larger branches and stems (Hakkila 1989). The ash content in barks of softwoods is reported to be approximately 2% whereas in hardwoods it averages 5%. Therefore the proportion of bark in LR is closely related to the ash content. This also explains the large difference in the ash content between softwood and hardwood in small branches compared to larger stems. In fact, our result suggests that in larger stems, softwood ash content may exceed that of hardwood.

SUMMARY

This study demonstrated that quality of logging residue changes during storage and consequently the net energy yield. The moisture contents (OD basis) ranged from 14.1-35% in FT roadside slash piles and 13.9-40.7% in CTL blocks. There was a significant drop in moisture content after 1 year of storage. Hardwood windrow piles showed lower moisture content than hardwood beehive piles but such generalization could not be made in softwood piles. Smaller diameter logging residue displayed lower moisture content and higher thermal value but higher ash content as well. Softwood species demonstrated higher thermal value, lower moisture content and lower ash content. The thermal values ranged from 19.5 to 23.1 $MJ \cdot kg^{-1}$ and ash content ranged from 0.4% to 8.4% for all species, components and number of storage years. However, density of the material has to taken in to account prior to determining the superior feedstock. Furthermore the handling practices can also influence the quality of biomass. It was observed in the field that there were soil contaminants in logging residues that can add to the ash content. Therefore, it is important that slash be handled with the proper equipment. Handling logging residues with blades of skidders should be avoided as it may mix in contaminants from the forest floor. Driving skidders or other equipments over logging residues can result in mud from tires on logging residue.

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GETTING MORE VALUE FROM THE TOLERANT HARDWOOD HARVEST THROUGH SORTING AND MERCHANDIZING

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ABSTRACT

Tolerant hardwoods are a significant component of the forests of eastern Canada and the northeastern United States. It is important to extract as much value as possible from the existing tolerant hardwood harvest to furnish an established wood manufacturing sector dependent upon quality raw materials. Pricing for tolerant hardwood logs is based upon the quality of the log which makes sorting by value a viable option for a harvesting operation. Marketing and selling the 'right' high quality log to the 'right' buyer can increase revenues to the forest operator and add value throughout the value chain as the logs work their way from manufacturers to end users.

We implemented a log value recognition program in an operational forest harvest in the Huntsville, Ontario region starting in 2008. A parallel marketing effort was made to sell logs to higher priced buyers. One year results indicate an increase in revenue of 12%/m^3 harvested partially resulting from a 15 fold increase in the amount of veneer recovered. There was an increase in the percentage sawlog recovery which benefited the local sawmill and the landowner received an extra $70,000 in stumpage. This win-win scenario was created through a company wide change in attitude towards value rather than volume driven rewards. Implications for the entire tolerant hardwood value chain indicate an increase in economic activity in excess of $10 million from this change in one forest harvesting operation. We estimate the Province of Ontario's opportunity loss from current under-recovery of veneer is in excess of $40 million annually. Some insights into factors causing this under-recovery are provided.

Keyword: Tolerant hardwoods, veneer, segregation, merchandizing

INTRODUCTION

The tolerant hardwood forest of South Central Ontario is a vast and valuable resource. Dominated by sugar maple and yellow birch, this forest is generally on site class 1 or 2 land with about 2,000,000 ha under Crown ownership and an equal amount privately owned. The Provincial Forest Inventory lists stands between 60 and 160 years old that grow on average 2.5 m^3/ha/year. These forests provide significant wildlife habitat, environmental products, and other socio-economic benefits that are difficult to quantify but form part of Ontario's forest management goals. The location close to the large population centers of Southern Ontario guarantees an involved public.

The forest also supports a well established forest products sector. In the 2004-05 harvest levels on Crown land totaled about 500,000 m^3 for tolerant hardwoods from 23,000 ha harvested under the single tree selection system (30-50 m^3/ha) or the shelterwood system (50-70 m^3/ha) (Stinson 2009). Unfortunately mill return data indicates only 1600 m^3 of hard maple veneer and 2400 m^3 of yellow birch veneer was directed to veneer mills. This low rate of veneer harvest (0.8%) is about half of the amount identified when detailed studies are undertaken (Stinson 2009). The under-recovery of veneer or other high value logs can lead to a substantial opportunity loss to the economy as multiplier effects work down the manufacturing chain.

FPInnovations initiated a project to see if a veneer recognition and segregation system would improve the veneer recovery rate and benefit the harvesters and millers of Ontario's tolerant hardwood forest. After an initial scoping period FPInnovations provided training and assistance to Tom Fisher Logging Ltd of Huntsville, Ontario who undertook a change in his operations to recognize, segregate, concentrate, and merchandize higher-value logs from his Crown land harvests. This paper provides some results from that project along with insight into factors that might be suppressing the veneer yield from Ontario's Crown owned tolerant hardwood forest. Benefits of directing the right log to the right mill at the right time are discussed.

IN TOLERANT HARDWOODS QUALITY IS JOB 1

Tolerant hardwoods have a somewhat unique characteristic in that the quality of a log can determine the price of a log. As long as the minimum size specification is met, there can be large differentials in price per unit volume depending upon the product (veneer, sawlog, and pallet/pulp/fuelwood) (Table 1). There can also be differences in price within a product category with slicer veneer and specialty added premiums over rotary veneer (Table 2). Prices per unit volume will generally increase by size for logs of the same quality (Table 3). There can be overlap at the top end of the sawlog category with the rotary veneer category as veneer logs can move down the progression; i.e. a veneer log can be sawn into lumber. Specific buyers might not always recognize and pay for all grades and some buyers might price based upon an upgrade from bucking off a defect near the end of a log. Tolerant hardwood product value is influenced by appearance and wood colour, grain, and figure can affect log price. In addition there might be differences in the measured volume of a log (scale). From a seller's perspective, all these factors can best be neutralized by getting competitive bids for the logs.

Table 1: Sample prices for hard maple logs, Jamesville, New York, USA, July 2008.

Log Grade	Diameter inside bark	Length (ft, in)	Quality	Price (US$/'000)
Veneer	16"	9'6"+	no defect	$2,000 to $6,000
Prime	12"	8'-16'4"	4 clear faces	$1000
#1	12"	8'-16'4"	3 clear faces	$700
#2	12"	8'-16'4"	2 clear faces	$350
Pallet	11"	8'-16'4"	sound, straight	$250

Table 2: Comparison of slicer veneer, rotary veneer, and sawlog price for a similar size hard maple log, upstate New York, USA, July 2008.

Log Grade	Diameter inside bark	Length (ft, in)	Quality	Price (US$/'000)
Standard slicer veneer	14"	9'6" or 10'6"	1/3 heart, no defect	$2500
Clear rotary veneer	14"	9'6" or 10'6"	1/3 heart, small defect	$1000
Sawlog clear	14"	8'-16'4" trim	One small defect	$800

Table 3: A purchaser's price list that includes sawlogs only, New Hampshire, USA, July 2008.

Log Grade	Diameter inside bark	Length (ft, in)	Quality	Price (US$/'000)
HM Prime	16"	10' – 16'	4 clear faces	$700
HM Select	14"	8'-16'	4 clear faces	$600

SEGREGATION, CONCENTRATION, AND MERCHANDIZING = VALUE-ADDED YARD

Segregation

The tolerant hardwood forest produces species and products with different prices making these forests good candidates for segregation. Segregating by species and/or product then moving the segregated products to different mills is a common practice in Ontario's tolerant hardwood forest. Segregation can take place at the stump, the landing, an interim yard, or a mill yard. Wherever the segregation takes place the difference in price must exceed the additional cost of the segregation for the system to work. If a Crown forest is licensed to a specific mill the segregation process might not be a market based system depending upon the arrangements between the Crown, the harvester, and the mill.

Concentration

High-value tolerant hardwood stems are few and far between in the bush making concentration a potentially option. Concentrating logs of similar characteristics at a central location facilitates merchandizing and makes it worth while for purchasers of rarer products to 'shop' at the yard. Multiple buyers can be invited to examine concentrated wood providing additional marketing opportunities for the seller. Concentration can include a single harvester's wood or multiple sources combined together with some sort of log tracking system to ensure all are paid fairly. Crown regulations in Ontario require Crown and Private land wood be kept separate and not intermixed in a yard. Again the cost of concentrating must be less than the increase in revenue received.

Merchandizing

Merchandizing involves altering log characteristics to meet buyer specifications or simply finding buyers for particular logs. Merchandizing yards can provide a better environment for re-manufacturing than in the bush where space might be limited and machinery not ideal for handling the products. Merchandizing yards also allow for marketing 'waste' products that would otherwise be left in the bush or at the landing. Again the increase in revenue must exceed the cost.

Value-added yard

Combining all three (segregation, concentration, and merchandizing) in one yard can be termed a value-added yard. Traditionally these activities are undertaken at a satellite yard which can be moved as the source of wood changes during the course of operations. The location of the yard must be carefully considered as product handling and trucking costs can be significant. In a free-market system, the implementation of a value-added yard must be cost competitive against installing similar activities at other steps in the wood processing chain.

In our implementation with Tom Fisher Logging Ltd. an in-bush recognition and recovery system was implemented for higher-value logs. Low value material was slashed and moved directly from the woods to the mill. Higher value material was brought to the value-added yard which was centrally located on a main highway near Huntsville Ontario (Figure 1). It was expected the yard might have to move if the woodlands being harvested shifted.

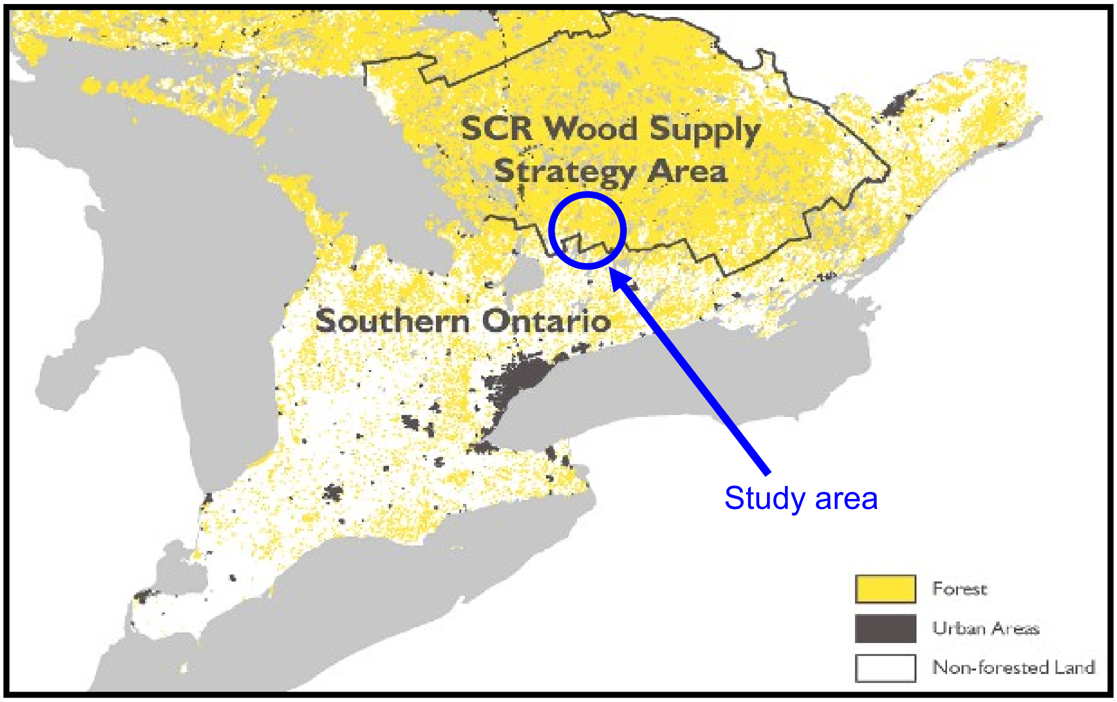

Figure 1: Study location and South Central Region of the Ontario Ministry of Natural Resources.

RESULTS

Differences in log prices

We investigated the differences in pricing by undertaking a virtual auction of 73 logs in the fall of 2008. All logs were identified and slashed in the bush and brought to a centralized yard near Huntsville, Ontario during a two week period. Two veneer buyers were invited individually to provide a scale, grade, and price for each log. One buyer was the traditional purchaser from a regional rotary mill who scaled using the Ontario Log Rule. The other purchaser was a broker from the US who scaled using the International Log Rule. Prices were normalized for the US dollar exchange rate at the time and any differences in trucking costs borne by the seller. A standard sawlog price was calculated at the normal bush run rate in place at the time. There were 40 yellow birch logs and 33 sugar maple logs in our test.

Interestingly if we sold all the logs to either of the two veneer purchasers our revenue was virtually identical ($7,997 vs. $8,180). Either veneer purchaser paid vastly more (average of $8,089) than if we did not segregate by product and sold all the logs as bush run sawlogs to the local sawmill ($1,900). We did not track the additional costs of identifying, segregating, and merchandizing the veneer logs to determine if segregation was profitable but the large difference in revenue over sawlogs was believed to eclipse the additional segregation costs (Hamilton and D'Eon 2010).

When we broke down the comparison by veneer purchaser we found approximately 1/3 of the logs had little difference in price (less than 25% difference), 1/3 had a moderate difference in price (26-100%), and 1/3 had a large difference in price (as much as $225 for a log). If we merchandized and sold each log to the higher bidder per log we would sell 42 logs to buyer A and 31 logs to buyer B for a total revenue of $10,175; an increase of 26% over selling the lot to either buyer. Differences were not one directional; i.e. either purchaser was equally likely to outbid the other. Buyer A bid higher on more sugar maple and Buyer B was more likely to purchase the yellow birch.

We did find differences in scaling of 11% which exceeds the normal standard of 5-7% for differences in the Ontario and International Log Rules but rarely explained the differences in price per log (Hamilton 2011). We found minor differences in log grade (+/- one grade) for 70% of the logs. We did find differences of three grades for 12% of the logs and differences of two grades for 18% of the logs which explained quite a bit of the differences in price. Specific buyers did not always recognize or pay for what another buyer found as a valuable characteristic.

Extra revenue from a year of running the value-added program

Tom Fisher Logging Ltd. ran the value-added program and yard for the 2009-2010 year (April 1st to March 31st). The program involved an in-bush recognition and sort along with concentrating and merchandizing at a central yard. The recognition started at the stump with the operators identifying and protecting high-value stems so they were not damaged prior to arriving at the landing. At the landing the slasher operator identified and bucked for value and set aside high-value pieces. Regular sawlogs, lower value pulp and fuelwood were handled as in previous years. An export permit was obtained from the Ontario Ministry of Natural Resources so some veneer logs could be exported to the United States. The traditional rotary veneer buyer was given first access to the rotary logs.

Prior to running the value-added program the logger was focused on volume recovery as payment was made to him by the volume harvested and not so much by value. Using the previous volume focused year as a comparison, the logger received 11.9% more revenue per unit volume of wood moved with the value-added program (Table 4). The percentage of veneer recovered went up 15 fold approaching the amounts obtained under experimental conditions and double the provincial average. The low value material percentage and revenue went down 14% and the sawlog material went up 13%. There were several additional side benefits including a more engaged employee team, less trucking, and less maintenance of equipment (Hamilton 2011). The trial was not designed to quantify the net profitability for the logger so we can only comment on the increase in revenue. The land harvested was part of the managed forest of that part of Ontario and there was no evidence the sites were any better in the value-added year than the previous year.

Table 4: Comparison of logger's annual revenue focused on volume production vs. focused on value production for a single year's harvest of 59,900 m^3.

Product	Product price ($/m^3)	Product split focused on volume (%)	Revenue when focused on volume	Product split focused on value (%)	Revenue when focused on value
Pulp/ fuelwood	$43	65.0%	$1,674,000.	50.8%	$1,308,000.
Sawlog	$72	34.9%	$1,505,000.	47.6%	$2,053,000.
Veneer	$207-218	0.1%	$12,000.	1.6%	$209,000.
Total:		100%	$3,192,000	100%	$3,570,000

Marketing was a major part of the program and Tom Fisher Logging Ltd. rapidly developed markets for various materials including figurewood, slicer veneer, and shorts (Table 5). These markets had not previously received wood from this part of the province. In the previous year only 100 m^3 of rotary veneer had been recovered in Tom Fisher's operation. The traditional buyer benefited from an increased supply that was concentrated in one place. The Crown received increase stumpage dues of $70,000 as the provincial rates vary by product and the increase in sawlog and veneer recovery shifted wood to the higher stumpage matrix (Hamilton 2011). Exports to the United States totaled only 149 m^3 from a 59,900 m^3 harvest (0.25%).

Table 5: Veneer markets and shipments 2009-2010.

Veneer buyer	Total volume (m^3)	Average price ($/m^3)	Maximum price ($/m^3)
Columbia, rotary, Rutherglen, Ont.	614	$207	$465
Gravenhurst, specialty, shorts, Gravenhurst, Ont.	156	$142	$305
Freeman, specialty slicer, Kentucky, USA	149	$322	$1120
Miller, specialty, figurewood, New Brunswick	37	$311	$1700
2009-10 Total	956	$218	

DISCUSSION

Recognizing, segregating, and moving the 'right' log to the 'right' mill at the 'right' time creates jobs and generates wealth. This is especially true in the tolerant hardwood forest where product and quality within a product can quickly change the economic potential of the wood. Veneer produces more milling jobs per m^3 than sawlogs or pulp and high value veneer even more so

(Table 6). High value logs are in short supply and mis-directing a log to a lower end product mill reduces the capacity of the forest products sector to generate positive economic returns (OMNR 2003). Estimates of the value to the economy generated per unit volume are difficult to obtain but a study in Indiana found the end products exceed \$50 / bd ft of input or approximately \$10,000 / m^3 (Swain 2006). Data from Quebec indicate approximately half that value (Clement 2005). Both these studies included sawlogs and veneer. Should Ontario return to a 1.6% veneer recovery rate for sugar maple and yellow birch and mill those logs in Ontario we estimate an additional \$40 million of economic activity would be generated for the province.

Table 6: Roundwood required per employee for various hardwood product mills.

Mill location	Product produced	m^3 used /year	Number of employees	m^3 /job
Durham	slicer veneer	30,000	415	72
Rutherglen	rotary veneer	50,000	320	156
Sault Ste. Marie	paper	400,000*	400	1000
Huntsville	sawlogs	125,000*	100	1250

*plus chips and other by-products.
Data source: OMNR 2005

The situation in Ontario is improving. Ontario switched from diameter limit harvesting and other systems to the single tree selection system in the mid 1970's and early 1980's for Crown owned tolerant hardwood stands. The selection system has been shown to improve quality in tolerant hardwoods and we expect to see these improvements in future harvests (Strong et al. 1995). Studies of tree grade to log grade and eventual board grade are lacking but the few undertaken clearly indicate the improved economics of managing tolerant hardwoods for quality (Fournier et al. 2006, Fortin et al. 2009). Logging damage during harvest can diminish these improvements and must be minimized (Morneault et al. 2007). Presentations at a recent Ontario workshop indicate corrections have been made to realize the gains from proper logging and single tree selection (D'Eon 2011). As Ontario's tolerant hardwood forests improve over time it will be important to ensure mechanisms are in place to recover the additional value created and value-added yards may play an increased role in the future.

CONCLUSIONS

Segregation, concentration, and merchandizing have been demonstrated as valid strategies to improve the value-added to Ontario's tolerant hardwood harvest. Proper markets at the two ends of the value range are equally important. Markets for low value material must be maintained so the stand improvement gains from the selection silvicultural system continue. Without markets for low value wood it is difficult to properly manage the stands. On the other end, high value specialty veneer logs that cannot be used to their full potential in Ontario's mills must be allowed to be easily marketed to their appropriate end-point. Without proper options for the high end material the anticipated gains will never be realized.

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MODELING WOOD BIOMASS PROCUREMENT FOR BIOENERGY PRODUCTION AT THE ATIKOKAN GENERATING STATION IN NORTHWESTERN ONTARIO

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ABSTRACT

Efficient procurement of wood biomass increases the effectiveness of biomass supply-chain management for bioenergy production. In this paper, a decision support system for planning the logistics of wood biomass procurement for conversion to bioenergy at the Atikokan Generating Station (AGS) in northwestern Ontario is developed. The model is based on a non-linear dynamic programming method. The model estimates optimal quantity and type of wood biomass supplied to the AGS based on its historical monthly power generation schedule. The two-way travel times from all depleted forest cells (19,315 cells) of 1 km^2 size to the AGS were determined, and cost from each cell was calculated using a previously developed road network optimization model. The model selects optimal harvesting volume from each forest cell in order to meet feed stock requirements for given monthly production schedule, and calculates the costs for biomass procurement. The model provides a global optimal solution for an annual planning horizon. Different cost scenarios are analyzed through sensitivity analyses.

Keywords: Biomass; logistics; optimization; road network; supply chain management.

INTRODUCTION

Biomass has great potential to be converted into renewable bioenergy, which not only has the advantage of reducing greenhouse gas (GHG) emissions, but also ensures a sustainable supply of energy that provides energy security and increased rural economic activities (Ediger and Kentel 1999, Ushiyma 1999, Berndes *et al.* 2003, Nagel 2000, Pari 2001, Gen and Smith 2006). In order to assess the economic feasibility of bioenergy production, it is important to understand and improve both the technological process of biomass to bioenergy conversion and the efficiency of the biomass supply chain.

A geographic information system (GIS) can be integrated with mathematical programming methods to develop a decision support system (DSS) for optimally supplying wood biomass for energy production (Noon 1996, Graham *et al.* 2000, Voivontas 2001, Freppaz *et al.* 2004, Ranta 2005, Geijzendorffer *et al.* 2008, Sylvain *et al.* 2009). Previous studies have developed optimization tools either using GIS or mathematical programming for forest biomass harvesting and procurement (Mitchell 2000, *Davide et al.* 2005, Sylvain *et al*. 2008, Rentizelas *et al.* 2009). Kaylen *et al.* 2000 developed a nonlinear programming model that incorporates competition between economies of scale in biomass feedstock production and transportation cost for a single ligno-cellulosic ethanol plant. Graham *et al.* (2000) used a GIS model to optimize the location of a biorefinery based on minimizing the cost of biomass supply.

However, none of these studies have used an integrated dynamic modeling approach. This study is an attempt to fill this gap. In this paper, a decision support system for planning the logistics of wood biomass procurement for conversion to bioenergy at the Atikokan Generating Station (AGS) in northwestern Ontario is developed. The model is based on a non-linear dynamic programming method using General Algebraic Modeling System (GAMS) computer software. The model is used to estimate optimal quantity and type of wood biomass supplied to the AGS, a proposed biomass-based power generating station, based on AGS's historical monthly power generation schedule.

METHODOLOGY

The research area (324 km x 516 km or 167,184 km^2) of this study consists of eighteen forest management units (FMUs) of northwestern Ontario that can potentially supply biomass feedstock to AGS (Figure 1). A non-linear optimization programming model for supplying wood biomass to AGS was developed using GAMS software (Appendix 1). GIS data were collected from Sustainable Forest Licence (SFL) holders and consultant companies in the formats of shapefile and geodatabase (Abitibi-Bowater Inc. 2009, GreenForest Management Inc. 2009, Greenmantle Forest Inc.2009, LIO 2010). ArcGIS was used to prepare spatial database in text format for the entire extent of research area. Three main spatial layers (forest landuse layer, forest depletion and cost layer) were prepared. A grid size of 1 km^2 was used for preparing these spatial layers. First a vector grid was developed, then this vector grid was converted to a raster layer, and finally a text file was developed from the raster layer. Each cell represents a feature. Different data input methods were followed for different types of features. ArcGIS was used to compile, clean and analyze spatial data and to prepare text files database (Nichols 2004, ESRI 2010).

A raster layer of forest landuse class was developed using the dominant type of data input method (ESRI 2010). In this method, the grid code entity was assigned to each cell for different landuse categories (1= productive forest, 2 = water/lake, and 3 = other landuse). The percent occurrence method was used for preparing the depletion layer. In this method, a code number was assigned to a grid cell depending on its depletion percentage: 1 represents 100% depletion, 2 is 80% to 100% depletion, 3 is 60% to 80% depletion, 4 is 40% to 60% depletion, 5 is 20% to 40% depletion, 6 is 0% to 20% depletion, and 7 is no depletion. The raster layer of the road network for the research area was developed using the presence/absence method of data input (ESRI 2010). A grid code was assigned depending on the presence of type of road in a cell. The grid codes for different road classes include: highway-I = 1, highway-II = 2, primary forest road = 3, secondary forest road = 4 and tertiary forest road = 5. If no road was present, grid code 9 was assigned to the cell. The raster layer of the road network was converted to ASCII (.txt) format. A road network optimization program coded in Visual Basic was used to prepare a cost layer for transporting wood biomass from each cell through the road network to the AGS. The location of the AGS was used as a sink node in the text files. Empty vehicle driving speeds of 90, 80, 60, 40 and 30 (km/hour) and loaded vehicles driving speeds of 90, 70, 50, 30 and 20 (km/hour) were used for highway-I, highway-II, and primary, secondary and tertiary forest roads, respectively. A truck load size of 50 m^3 of wood biomass and an operating rate of \$85/hour was used. A fixed time of 2.5 hours was considered for loading, unloading and delays per trip. The cost layer for transporting wood biomass to AGS was established using minimum travel time from each road cell of the research area to the AGS.

Forest landuse, depletion and cost layers were used as data input in the network optimization model to calculate the cost of transporting wood biomass from each cell (1 km^2 area) of productive forest to AGS. The theoretical availability of forest harvest residue (FHR) and unutilized and under-utilized wood (UUW) in the productive forests of northwestern Ontario is about 60 m^3/ha each (Alam *et al.* 2011). The total number of depleted forest cells (0% to 100% depletion) over the seven year study-period (2002 to 2009) was 19,315. We also assumed that 1 m^3 of wood biomass is the equivalent of 0.876 green tonnes (gt) of biomass. Two-way travel times from all the depleted forest cells to AGS were determined using a previously developed road network optimization model. The model then selects an optimal harvest volume from each forest cell in order to meet the feed-stock requirements for given monthly production schedule, and calculates the costs of biomass procurement. The model is non-linear due to its inherent nature of solution procedure in GAMS, where one endogenous variable (amount of biomass to be harvested in the next period) is determined with the help of another endogenous variable (the amount harvested in the previous periods). The model is dynamic in the sense that it provides a global solution to the entire planning horizon of 12 months operation of the power plant by simultaneously taking the capacity constraints and requirements for each month into account.

The other assumptions used in base scenario (BASE) include: harvesting factor (HF) of 67%; harvesting and grinding/chipping (processing) cost for FHR of \$26; harvesting and grinding cost for UUW of \$31; conversion efficiency (CE) of power plant as 35%; and moisture content (MC) of wood biomass of 30%. The heat value of wood biomass was taken as 19.6 GJ/ODt; and 3.6 GJ/MWh was used to convert the heat value to electricity unit. The monthly amounts (MWh) of electricity production over the planning horizon of one year are shown in Appendix 1 (Sygration 2011). The four alternate scenarios, such as Increased Harvesting Factor (INHF), Increased Conversion Efficiency (INCE), Increased Moisture Content (INMC) and Increased Harvesting and Grinding Cost (INHG) were run to test the sensitivity of HF, CE, MC, and harvesting and grinding/chipping cost, respectively.

RESULTS AND DISCUSSION

The model provides a global optimal solution for a one year planning horizon by minimizing the objective function of biomass procurement costs (harvesting, processing and transportation) based on wood biomass availability in each cell. In the BASE scenario, out of 100,061 forest cells, only 2,959 cells were selected for collecting FHR and 208 cells were selected for harvesting both FHR and UUW to fulfill the annual wood biomass demand by AGS. The forest cells selected for collecting FHR were mainly located in five FMUs (Crossroute Forest, Sapawe Forest, Dog River-Matawin Forest, Wabigoon Forest and Dryden Forest) (Figure 1). Only one forest cell from the Lakehead Forest was selected for FHR collection. All forest cells selected for harvesting UUW were located in the Crossroute Forest. The other twelve FMUs were not selected for harvesting wood biomass for energy production. Based on the historical monthly generating production the AGS requires 397,867 gt of biomass annually to produce 507,037 MWh of electricity. For this electricity production at the AGS the total annual and unit production costs were found to be $14,310,557 and $28.17/MWh, respectively (Table 1). It was found that FHR and UUW were collected first from the cells which were closer to AGS, and then the model selected farther cells in the later months of the year. The behavior of the model is consistent with a priori hypothesis of mode of biomass collection as it is not economical to transport biomass over long distances.

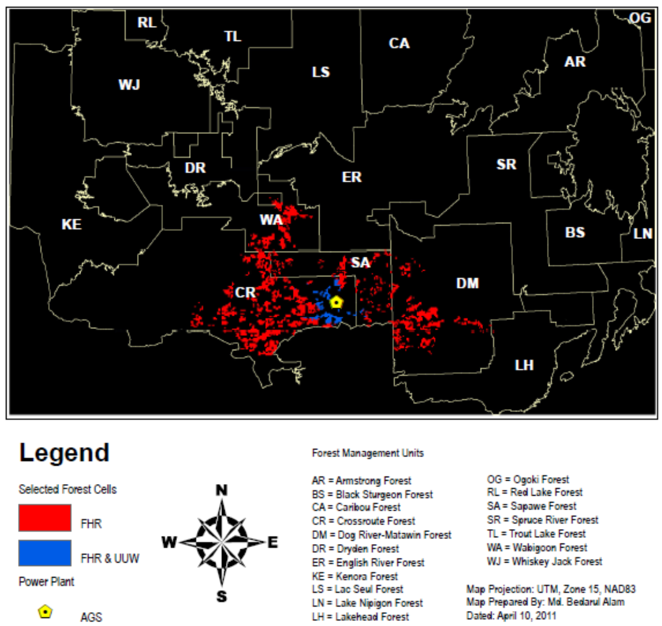

Figure 1: Forest cells selected for harvesting

The results of the five sensitivity analyses are presented in Table 1 and Figure 2. In INHF (with 72% HF) 2837 forest cells were selected for FHR and 171 forest cells were selected for UUW. In comparison with the BASE, unit cost of electricity production is 0.37% less in INHF because more wood biomass could be harvested from the forest cells at lesser transportation cost to fulfill the demand of wood biomass feedstock at AGS. In INCE (with 40% CE) the number of forest cells selected for FHR and UUW were 2735 and 144, respectively. The wood biomass harvested in INCE was 348133 gt, total electricity production cost was $12,434,763, and unit cost of production was 24.58 $/MWh, which were 12.5% , 13.11% and 12.76%, respectively lower than in the BASE scenario. Due to higher CE, the amount of wood biomass feedstock was reduced to produce the same amount of power at the AGS as compared to other scenarios (Berndes *et al.* 2003, Koppejan 2007, Alam *et al.* 2009).

Table 1: Sensitivity analysis for increased harvesting factor, conversion efficiency, moisture content, and harvesting and grinding costs

Category/Scenario	BASE	INHF	INCE	INMC	INHG
Wood Biomass (gt)	397866.78	397866.78	348133.43	433663.54	397866.78
Procurement Cost ($)	14310556.54	14256641.52	12434763.17	15669451.51	15382602.59
Electricity (MWh)	507037.00	507037.00	507037.00	507037.00	507037.00
Unit Cost ($/MWh)	28.17	28.07	24.58	30.80	30.24

In INMC (with 35% MC) 3,123 forest cells were selected for FHR and 260 forest cells were selected for UUW. The wood biomass harvested in INMC was 9% higher, total electricity production cost was 9.5% higher, the unit cost of production was 9.32% increased, as compared to the BASE scenario. Due to higher MC, the net amount of heat value is lower in wood biomass (Nurmi 1999, Berndes *et al.* 2003, Koppejan 2007) resulting in a higher volume of wood biomass required to produce the same amount of electricity. In INHG the harvesting and grinding/chipping cost was increased by 10% for both FHR and UUW. Since the harvesting and grinding/chipping cost for UUW became much more than FHE in INHP, fewer forest cells for UUW (254) and more forest cells for FHR (3167) were selected than in the BASE scenario. The total cost of electricity production ($15,382,603) and the unit electricity production costs (30.24 $/MWh) were the second highest in INHG than in other scenarios. Previous studies show similar results (Berndes *et al.* 2003, Tatsiopoulos and Tolis 2003, Sokhansanj *et al.* 2006).

These five scenarios provide an interesting opportunity for further research on improving the technological processes of biomass to bioenergy conversion as well as using efficient harvesting techniques to reduce the total logistics cost. Similar suggestions have been made by previous studies in the U.S. (Gan and Smith 2006).

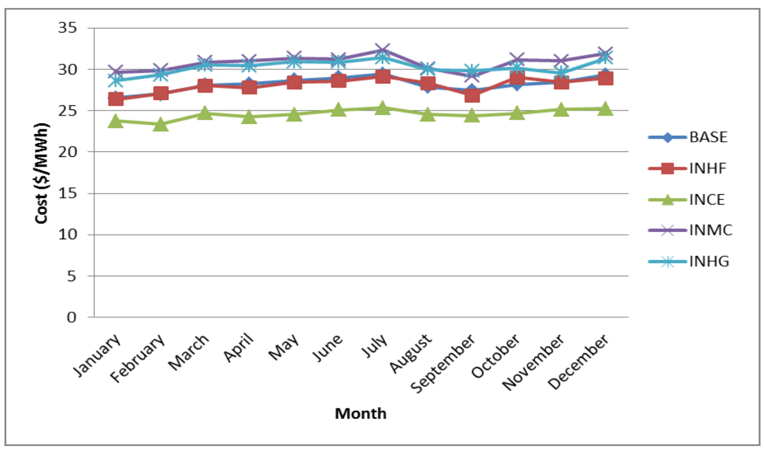

Figure 2: Sensitivity analysis for increased harvesting factor, conversion efficiency, moisture content, and harvesting and grinding costs

CONCLUSIONS

The complexities of biomass feedstock procurement and supply chain for the Atikokan power generating station in northwestern Ontario were handled in the most efficient and cost effective way by developing a non-linear dynamic programming model. The model provided global optimal solutions consisting of forest cells and types of wood biomass selection by minimizing the costs of wood biomass harvesting, processing and transportation from available forest cells to the power generating station. The results suggest that the demand of FHR and UUW biomass for AGS could be fulfilled optimally by collecting the available FHR from 2,959 cells and UUW from 208 cells out of 19,315 forest cells available in the research area. The model also has the potential to analyze the effects of changes in important parameter and choice variables, thereby providing important information for decision support in reducing overall procurement costs over time.

This model could be further improved by incorporating data related to differences between tree species, forest types, moisture contents, heat values, harvesting methods, harvesting systems, and variations in the amount of seasonal and weekly power generation. Production of pellets in a distributed network could further reduce the transportation costs and feedstock requirements as pellets are a more energy dense biomass feedstock. Future versions of this model will reflect these improvements by incorporating new information and will help in developing an integrated decision support system for bioenergy production in northwestern Ontario.

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APPENDIX 1

```
$TITLE: DSS for wood biomass to electricity production in northwestern Ontario, Canada
SETS
    i       Months in a year /1*12/
*/ Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec /
    j       Forest cells /1 *19315/
$include c:\procurement\data_ags.txt
Table EP (i, *)   Monthly demand of electricity production in MWh
            Production
1           47746
2           74931
3           32293
4           7615
5           97280
6           73581
7           46799
8           42564
9           5822
10          26835
11          9974
12          41597
SCALARS
   CE    Conversion efficiency /0.35/
   ED    Energy density for oven dry tonne (ODT) biomass in GJ /19.6/
   MC    Moisture content in green biomass /30/
   EG    Equivalency of energy in GJ per MWh /3.6/
   PR    Harvesting and grinding costs for forest harvest residue (FHR) dollar per green tonne (gt) /31/
   PU    Harvesting and grinding costs for unutilized and underutilized wood (UUW) dollar per gt /26/
   HF    Harvesting factor /0.67/
PARAMETERS
    BD(i)   Monthly biomass required by power plant in gt
    IR(j)   Initial FHR availability in a forest cell
    IU(j)   Initial UUW availability in a forest cell;
    BD(i) = (EP(i,"Production") * EG) /((ED-0.2164*MC) * CE);
    IR(j) = (BMS(j, "FHR") * HF)/7;
    IU(j) = (BMS(j,"UUW") * HF)/7;
    Display  BD, IR, IU;
VARIABLES
    XR(i,j)         Amount of FHR harvest from a forest cell (gt per month)
    XU(i,j)         Amount of UUW harvest from a forest cell (gt per month)
    TB(i)           Monthly total amount of biomass harvest in gt
    TPC             Total biomass procurement cost in Dollar
    RT(i,j)         Total monthly FHR avialabity in a forest cell in gt
```

```
   UT(i,j)          Total monthly FHR availability a forest cell in gt;
POSITIVE VARIABLES
   XR, XU
EQUATIONS
   EQOBJ            Equation for calculating objective function value
   EQBD(i)          Monthly requirements of biomass constraint
   EQTB(i)          Calculating equation for monthly biomass harvest
   EQRT(i,j)        Constraint to FHR availability
   EQUT(i,j)        Constraint to UUW availability
   EQRT1(i,j)       Constraint to FHR availability
   EQUT1(i,j)       Constraint to UUW availability;
   EQOBJ..  SUM((i,j), XR(i,j)* BMS(j, "CADpTBM")) +
                SUM((i,j), XU(i,j)* BMS(j, "CADpTBM")) +  SUM((i,j), XR(i,j)* PR) +
                SUM((i,j), XU(i,j)* PU) =E= TPC;
                RT.FX("1",j) = IR(j);
                UT.FX("1",j) = IU(j);
   EQTB(i).. SUM(j, XR(i,j)) + SUM(j, XU(i,j)) =E= TB(i);
   EQRT(i,j).. XR(i,j) =L= RT(i,j);
   EQUT(i,j).. XU(i,j) =L= UT(i,j);
   EQRT1(i+1,j).. RT(i+1,j) =E= RT(i,j)- XR(i,j);
   EQUT1(i+1,j).. UT(i+1,j) =E= UT(i,j)- XU(i,j);
   EQBD(i)..  TB(i) =G= BD(i);
MODEL DSS /ALL/;
DSS.ITERLIM  = 500000;
DSS.RESLIM   = 45000;
SOLVE DSS MINIMIZING TPC USING NLP;
PARAMETERS
   REPORT1 (*,*) FHR biomass harvested from different forest cells
   REPORT2 (*,*) UUW biomass harvested from different forest cells
   REPORT3 (*,*) Monthly total amount of biomass harvest in gt
   REPORT4 (*,*) Monthly total cost of biomass feedstock procurement
   REPORT5 (*,*) Monthly per unit cost of biomass procurement;
   REPORT1 (j,i) =  XR.L(i,j);
   REPORT2 (j,i) =  XU.L(i,j);
   REPORT3 ("Total Harvest",i) = sum (j, (XR.L(i,j)))+sum (j, (XU.L(i,j)));
   REPORT4 ("cost",i) =  SUM(j, (XR.L(i,j)*(BMS(j, "CADpTBM")+PR)))+
                   SUM(j, (XU.L(i,j)*(BMS(j, "CADpTBM")+PU)));
   REPORT5 ("Per MWh cost",i)= REPORT4("cost",i)/EP(i, "Production");

  Display report1, report2, report3, report4, report5;
```

SOLVING A MULTI-PERIOD LOG-TRUCK SCHEDULING PROBLEM WITH COLUMN GENERATION

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ABSTRACT

We present here a multi-period routing and scheduling problem that arises in the Canadian forestry industry. In this tactical problem, mill demands of various wood types are given for every 2 week period in a 52 week schedule. Also given are the harvested quantities of each wood type at each forest site. Wood can be stored at the forest for a given length of time prior to delivery at a financial cost. The objective is to determine the quantity of wood that should be delivered from forest to mill at every period, and the determination of routes traversed by the log-trucks delivering the wood, all while minimizing total cost. We model this problem as a mixed integer linear program and solve via column generation with the columns, representing log-truck routes, generated through the resolution of resource constrained shortest path problems. We then enforce integrality to find near-optimal integer solutions. The methodology is tested on a case study from industry.

Keywords: Forestry, vehicle routing, pickup-and-delivery, column generation, dynamic programming

INTRODUCTION

According to *Natural Resources Canada*, Canada has 402.1 million hectares of forest and other wooded land, making up approximately 10% of the world's forest cover. It is therefore unsurprising that we are the world's largest exporter of forest products: in 2008 the value of all exports from this industry was over 30 billion dollars. Overall, the forest industry accounts for approximately 2% of national gross domestic product. When dealing with an economy of this scale, it is clear that performing all operations as efficiently as possible can lead to tremendous financial savings. Therefore it is a necessity that the use of optimization models and methods are commonplace in this industry, both for the obvious economic, and also environmental reasons.

Because of the geographical nature of Quebec, transportation accounts for approximately 30% of the total cost of wood. The average distance between the forest, where the wood is collected, and the mills, to which it is delivered, is approximately 150 km. However, as significant as this aspect of the supply chain is, most Canadian forest companies have a planner derive the truck schedules manually.

The contribution of this paper is to define a specific multi-period log-truck scheduling problem over a one year horizon motivated by a specific problem that arises in industry. This problem takes into account both wood storage between periods, and routing decisions in each period.

The paper is organized as follows. In section 2 we will give a brief literature review. In section 3 we define the problem. In section 4 we discuss our methodology. In section 5 we give the computational results, and finally section 6 concludes the paper.

LITERATURE REVIEW

An introduction to optimization in the forestry industry is given in (Rönnqvist 2003). The author distinguishes between the strategic, tactical, and operational planning levels. At the strategic level (over 5 years), the major decisions to be made are long term harvesting decisions, road building and upgrading, and investment planning. At the tactical level (between 6 months and 5 years) the major decisions are the creation of annual harvest plans, road upgrading, equipment utilization, and annual production planning. Finally, at the operational level (between 1 day and 6 months) the major decisions are those dealing with harvest crew scheduling and log-truck scheduling.

The log-truck scheduling problem (LTSP) is a classic problem, where the goal is to move logs from supply points (forest sites) to demand points (mills) at minimum cost. Transportation decisions are of course not unique to the forestry industry, and the LTSP is a generalization of other well-studied problems. In the vehicle routing problem (VRP), a set of clients must each be visited exactly once by a vehicle, all of which are based at a common depot. Each vehicle must not have a cumulative demand on its route that exceeds its capacity. A further generalization of the VRP is the pickup-and-delivery problem (PDP). For surveys on vehicle routing problems and pickup-and-delivery problems we direct the reader to (Toth and Vigo 2001, Berbeglia et al. 2007).

The pickup-and-delivery problem encountered in the forestry industry has similarities to several more specific problems. In the pickup-and-delivery problem with time windows (PDPTW), transportation requests must respect time window restrictions at customer locations. Additionally, most pickup-and-delivery problems seen in the literature have each customer serviced by exactly one vehicle. In the forestry industry; however, a single visit by a single vehicle is almost always insufficient to transport the entire demand. Therefore, multiple visits are required by either one or many vehicles. In the literature, problems with this feature are referred to as split load vehicle routing problems (SLVRPs) (Dror et al., 1994).

There is much literature devoted specifically to the LTSP. EPO (Linnainmaa et al. 1995), a knowledge-based system that outputs a weekly schedule for each truck, was developed in 1995.

Column generation has been applied to the log-truck scheduling problem (Palmgren et al. 2004, Rey et al. 2009). In the former, the subproblem was solved using a *k*-shortest path algorithm and a branch-and-price heuristic was used to find integer feasible solutions; while in the latter, dynamic programming was utilized in the subproblem and branch-and-bound was used after solving the relaxation with the column generation. In (Gronalt and Hirsch 2007), the authors applied a tabu search strategy to a restriction of the LTSP in which the number of trips between each forest site and mill is known. In (El Hachemi et al. 2011a), the same restriction is tackled using integer programming to generate optimal routes, and constraint programming (CP) to schedule the trucks. The same authors (El Hachemi et al. 2011b) consider a weekly problem in which they assign forest supply to mills by solving a MIP, and they then use both CP and constraint based local search (CBLS) to schedule the trucks afterwards. In these final two works, an additional constraint present is the need to synchronize with log loaders at both the forest and mill.

PROBLEM DEFINITION

Given a harvest plan of multiple log assortments at multiple forest sites over a multi-period planning horizon, and mill demands over the same horizon, the decisions to be dealt with will be those involving when to deliver the harvested wood and additionally the decisions of creating log-truck routes in order to deliver the produced logs to the mills at an overall minimal cost, which is made up of both routing and storage costs. We note that the given harvest plan has forest-mill assignments defined, that all volumes of wood are in cubic meters (m^3), and that the truck fleet is homogeneous. In this problem, we also deal with trucks that are equipped with log loaders, so no synchronization is required.

In addition to satisfying mill demands and not exceeding the harvested quantities, several other constraints must be satisfied. There exists a given limit on the length of time wood can remain in the forest. This may vary by period, as wood deteriorates less quickly in the winter than in other seasons. With respect to routing, we assume that each period consists of a set of working days. On each working day, if a truck is to be used, it must begin and end its day at the same mill (a home base). The truck then alternates between forest sites where it loads woods, and mills, where it then unloads. Truck capacity cannot be exceeded, and the truck cannot carry different assortments at the same time. Additionally, each mill has operating hours over which it can receive wood. However, a truck can leave a mill before it opens and return to a mill after it closes. The cost of each route is a function of the costs associated with driving, loading, unloading and waiting time. One may additionally impose a fixed cost on operating a truck on a day. We also must ensure a balanced schedule over the horizon: each period must employ a number of daily truck routes that does not stray too far from the mean over all periods.

Mathematical Formulation

Let us define F to be the set of forest sites, M to be the set of mills, L to be the set of log assortments, T to be the set of periods in the planning horizon, and J to be the set of all feasible log-truck routes. We also partition J by home mill, into J_m for all m in M. We now define the input data of the model:

- h_{fmlt} : the quantity of assortment l harvested at forest f tagged for mill m in period t,
- d_{mlt} : the demand of assortment l at mill m in period t,
- i_{fml} : the initial inventory of assortment l at forest f tagged for mill m,
- i_{ml} : the initial inventory of assortment l at mill m,
- w_{flt} : the maximum storage time at forest f of assortment l harvested in period t,
- k_l : the truck capacity of assortment l,
- c_{flt} : the per unit storage cost of assortment l at forest f in period t,
- c_{mlt} : the per unit storage cost of assortment l at mill m in period t,
- $\varepsilon \in [0,1]$: the allowable deviation per period from the mean number of routes,
- c_t : the fixed cost of operating a truck on a day,
- c_j : the cost of route j,
- a_{fmlj} : the number of trips from forest f to mill m carrying assortment l on route j.

The variables of the model are given below:

- y_{jt} : the number of times route j is traversed in period t,
- Tr_{mt} : the number of daily truck routes based at mill m in period t,
- z_{mlt} : the quantity of assortment l stored at mill m entering period $t \leq |T|+1$,
- z_{fmlt} : the quantity of assortment l stored at forest f tagged for mill m entering period $t \leq |T|+1$,
- x_{fmlt} : the quantity of assortment l delivered from forest f to mill m in period t.

The problem can then be formulated as the minimization of the objective function:

$$\sum_{t \in T} \sum_{j \in J} c_j y_{jt} + \sum_{m \in M} \sum_{t \in T} c_t Tr_{mt} + \sum_{f \in F} \sum_{m \in M} \sum_{t \in T} \sum_{l \in L} c_{flt} z_{flt} + \sum_{m \in M} \sum_{t \in T} \sum_{l \in L} c_{mlt} z_{mlt} \quad (1)$$

subject to:

$$z_{ml0} = i_{ml} \qquad \forall m \in M, l \in L \qquad (2)$$

$$z_{fml0} = i_{fml} \qquad \forall f \in F, m \in M, l \in L \qquad (3)$$

$$z_{mlt} + \sum_{f \in F} x_{fmlt} - d_{mlt} = z_{ml,t+1} \qquad \forall m \in M, l \in L, t \in T \qquad (4)$$

$$z_{fmlt} + h_{fmlt} - x_{fmlt} = z_{fml,t+1} \qquad \forall f \in F, m \in M, l \in L, t \in T \qquad (5)$$

$$\sum_{w=1}^{w_{flt} | t-w \geq 1} h_{fml,t-w} \geq z_{fmlt} \qquad \forall f \in F, m \in M, t \leq |T|+1 \qquad (6)$$

$$\sum_{j \in J} k_l a_{fmlj} y_{jt} \geq x_{fmlt} \qquad \forall f \in f, m \in M, l \in L, t \in T \qquad (7)$$

$$\sum_{j \in J_m} y_{jt} = Tr_{mt} \qquad \forall m \in M, t \in T \qquad (8)$$

$$\sum_{m \in M} Tr_{mt} - \frac{1-\varepsilon}{|T|} \sum_{t \in T} \sum_{m \in M} Tr_{mt} \geq 0 \qquad \forall m \in M, t \in T \qquad (9)$$

$$\frac{1+\varepsilon}{|T|} \sum_{t \in T} \sum_{m \in M} Tr_{mt} - \sum_{m \in M} Tr_{mt} \geq 0 \qquad \forall m \in M, t \in T \qquad (10)$$

$$y_{jt}, Tr_{mt} \in Z^{+} \qquad \forall m \in M, j \in J_m, t \in T \qquad (11)$$

$$z_{mlt}, z_{fmlt}, x_{fmlt} \in \Re^{+} \qquad \forall f \in F, m \in M, l \in L, t \in T \qquad (12)$$

We denote this problem by *(P)*. The objective function (1) minimizes total costs associated with driving and storage. Constraints (2) and (3) set the initial inventories at the mills and forests, respectively. Constraints (4) and (5) link the storage variables of successive periods at the mills and forests, respectively. The non-negativity of all variables ensure that forest supply and mill demands are respected. Constraints (6) ensure that wood is not left at the forest longer than allowed. Constraints (7) force the quantity delivered to respect the capacities of all trucks making that trip. Constraints (8) fix the number of routes originating from each mill in each period. Constraints (9) and (10) ensure a balanced schedule in terms of the number of truck routes traversed per period. Finally, constraints (11) and (12) enforce the non-negativity of the variables, as well as discretize the variables that count log-truck routes. We denote by Z^{+} and $\Re^{+}$ the sets of non-negative integers and reals, respectively.

We also note that in many contexts, constraints (9) and (10) may be omitted in lieu of bounds on the Tr_{mt} variables to represent truck availability. This can be easily implemented into the current model. Additionally, there is no variable denoting the amount loaded at every forest on every route. This is done to dramatically reduce the size of the formulation, and this information can trivially be determined from a feasible solution in a greedy fashion.

METHODOLOGY

We propose to apply column generation to this problem, similar to the method used in (Rey et al. 2009). This approach must be generalized to a multi-period setting.

The Column Generation Procedure

To solve the linear relaxation of (*P*) via column generation, we must first determine an initial set of columns J' that makes the problem feasible. The most intuitive and simple route subset of J that guarantees to make the problem feasible is the set of out-and-back routes defined by (f,m,l) for f,m,l in F,M,L, respectively. We repeat this trip as many times as time windows will allow, and add this route as a column for every period t in which this trip is valid for the harvest plan and mill demands.

We denote this restricted master problem (P'), and propose to add feasible columns with a negative reduced cost by way of a set of subproblems. We create one subproblem for each home mill, and one for each period (hence having $|M||T|$ subproblems), solve, and add any found columns to the master problem. We then resolve the LP and iterate this procedure until no negative reduced cost routes remain. We finally restore integrality to the variables y and Tr and solve the resulting model as a MIP. We note that this method does not solve the original model exactly, as that would require the use of a branch-and-price algorithm (Barnhart et al. 1998). However, solving the linear relaxation to optimality does yield a lower bound, and we will see in the following section that we are still able to find integer solutions very close to this lower bound.

Defining the subproblems

After solving any master LP, we store the dual values associated with constraints (7) and (8), which we denote π_{fmlt} and λ_{mt}, respectively. Our search then begins for negative reduced cost columns. We propose to find these columns by performing a set of dynamic programming algorithms, one for each mill m in M and each period t in T.

To solve these subproblems, we must first construct a space-time network, which we denote $G=(V,A)$. In this space-time network we discretize the time dimension to a set of intervals $I=\{0,1,\ldots,I^{max}\}$, where I^{max} corresponds to the length of a working day. Let δ be the length of time, in hours, each interval in I corresponds to, and let $d(f,m)$ represent the discrete distance between any forest f and mill m, where the distance is measured in driving time plus (un)loading time.

We then define the network with vertex set $V=(M\cap F)\times I$ and arc set $A=A_w\cup A_u\cup A_l$, where the three partitions represent waiting, unloaded driving, and loaded driving arcs, respectively. The driving arcs also take into account (un)loading time, and are only included if they respect time windows at the forest and mill. Moreover, arcs of A_l are only included if f provides an assortment that m has a demand for. We can further presolve this network by period t to build a set of networks G_t. This involves removing vertices associated with forests that cannot be holding supply at t and any incident arcs. All networks G_t clearly have a topological ordering, which is identical to a chronological ordering with ties broken arbitrarily.

We then associate with each arc (u,v) a cost c_{uv}. When driving loaded, this cost takes into account the use of the dual value corresponding to the appropriate constraint (8). While there are potentially many log assortments that can be taken between that forest and mill, we create exactly one arc which corresponds to the assortment that yields the best (most negative) reduced cost. Let c_o and c_w be the per hour costs of a vehicle when operating and waiting, respectively. The arc costs of the network are then as follows:

$$
\begin{aligned}
c_{uv} &= \delta c_w && (u,v) \in A_w \\
c_{uv} &= \delta d(f,m) c_o && (u,v) \in A_u \\
c_{uv} &= \min_{l \in L} \left\{ \delta d(f,m) c_o - k_l \pi_{fmlt} \right\} && (u,v) \in A_l
\end{aligned}
$$

Any feasible route in period t can then be expressed as a path in network G_t between any two vertices representing home mill m at different times in the day. The reduced cost of this route will then be equal to the cost of the path minus the dual value λ_{mt}, which measures a fixed reduced cost associated with operating a truck from that mill in that period. An example space-time network and highlighted route on a small example, with many nodes and all arcs not appearing in the route removed for clarity, is given in Figure 1.

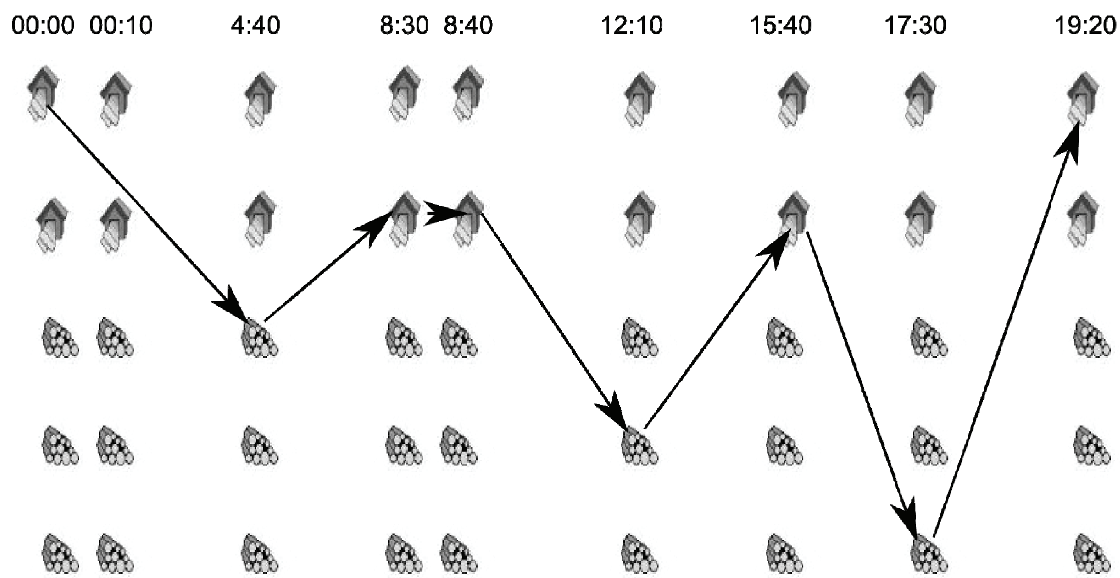

Figure 1: An Example Space-Time Network and Feasible Log-Truck Route

Solving the subproblems with dynamic programming

To find negative reduced cost routes to add to the master problem, we utilize a standard label setting algorithm (Cormen et al. 1990, Sec 24.2) for directed, acyclic graphs. In this algorith we associate with each vertex *v* a label *[pred*$_v$*, RC*$_v$*]*, which denotes the predecessor of *v* and the length (reduced cost) of the shortest path to *v*. For any period *t* and home mill *m*, we provide the algorithm NegativeRoutes() in Algorithm 1.

Algorithm 1 : NegativeRoutes()

1. **for all** $v \in V(G_t)$ **do**
2. $pred_v \leftarrow null$
3. **if** v corresponds to mill m **then**
4. $RC_v \leftarrow -\lambda_{mt}$
5. **else**
6. $RC_v \leftarrow \infty$
7. **for all** $u \in V(G_t)$ following the topological ordering **do**
8. **for all** $(u,v) \in A(G_t)$ **do**
9. **if** $RC_u + c_{uv} < RC_v$ **do**
10. $RC_v \leftarrow RC_u + c_{uv}$
11. $pred_v \leftarrow u$
12. **for all** $v \in V(G_t)$ **do**
13. **if** v corresponds to mill m**then**
14. **if** $RC_v < 0$ **then**
15. Iterate backwards and store path to v if non - dominated

Lines 1 through 6 initialize the labels. Lines 7 through 11 push through the graph and update labels as required. Lines 12 through 15 store all negative reduced cost routes from home mill . When we say that a path is non-dominated, we mean that if two routes are exactly the same in terms of locations visited, we only ever store the one with the least waiting time to break symmetries.

EXPERIMENTAL RESULTS

Our methodology was tested on a data set provided by the FERIC[1] division of FPInnovations. The problem is over a yearly horizon, divided into 26 periods of 14 days. There are 42 forest sites

1 The Forest Engineering Research Institute of Canada is a private, not-for-profit research and development organization whose goal is to improve Canadian forestry operations related to the harvesting and transportation of wood, and the growing of trees, within a framework of sustainable development.

providing 5 log assortments to 7 mills. The distances between forests and mills are approximately 1−4 hours, with loading and unloading times both being 40 minutes.

We modelled the algorithm in C++, and used Gurobi 4.5 as an LP and MIP solver. All Gurobi parameters were set to defaults, with the exception that the MIP tolerance in solving the final MIP was set to 0.1%. Also, at each master iteration, rather than add every negative reduced cost route to the LP, we added the best (most negative) 500 found. In discretizing the time dimension for the subproblem, we set the width of every interval to be 3 minutes, and hence a day had a time dimension of size 480.

On this case study, 24 master iterations were required. At each iteration, we were able to solve all subproblems in an average of 0.42 seconds, and hence were able to solve the relaxation to optimality in a matter of approximately 10 seconds. The MIP was then solved to optimality (within 0.1% of the derived lower bound) in 222 seconds.

As a basis for comparison, we also solved the root node LP (using only out-and-back routes) as a MIP to determine the savings generated by dynamically generating improving routes. Using the same MIP tolerance, the optimal solution found was approximately 5% greater than that found via column generation.

CONCLUSION

We have introduced a multi-period log-truck scheduling problem in which the objective to be minimized is a function of both truck operating and wood storage costs. We modelled this problem as a mixed integer linear program and solved the linear relaxation via column generation, using dynamic programming to solve the subproblems at each master iteration. Integer feasible solutions were then found via branch-and-bound after solving the linear relaxation to optimality. On a problem set provided by an industrial partner, the feasible integer solutions could be easily found within 0.1% of the continuous optimal solution, which shows that this methodology can be very useful in this field.

Future work involves extending this model to a heterogeneous truck fleet and synchronizing with log loaders in the case where trucks are not equipped with their own loaders. Another future goal is to synchronize the routing decisions with other aspects of the supply chain, such as harvest planning.

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A GENERIC PROCESS MODEL FOR DELIVERY SCHEDULING OF BIOFUELS IN SWEDEN

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ABSTRACT

According to the concept of Enterprise Architecture an alignment of Business and IT must be enabled to achieve supporting Information Systems. The first step in the development of an Information System is documenting the business process.

This study uses the Integration Definition for Function Modeling to formulate an interview study of 11 Swedish biofuel supplier and customers. The goal of this study is to clarify a generic sequence of activities performed within the delivery scheduling process and the information needed to execute the activities within process of Delivery Scheduling.

The result of the study is a one generic IDEF0- model for suppliers and two generic models for customers. These models include their respective information usage.

A CRUD matrix for the information processed is formulated based on the IDEF0-model.

The EA-approach results in a generic formulation of the business from an Information System point of view. This approach is a key to achieving alignment between business functions and supporting IT.

Keywords: Enterprise Architecture, IDEF0, CRUD matrix, function modeling

INTRODUCTION

The contribution of biofuels to the total consumption of energy in Sweden is today over 32 %, which makes it the largest energy source in Sweden (Svebio, 2010). The use of biofuels for energy consumption must increase to meet the goals for year 2020 set by the European Union. In order to do so improved Information Systems are needed to support the business processes within delivery scheduling between customers and suppliers. In development of supporting Information Systems the concept of Enterprise Architecture (EA) is applicable. According to EA an alignment of Business and IT must be enabled.

Enterprise Architecture is a recent discipline that has emerged mainly from the business and IT management perspectives and it is based on architectural frameworks. These frameworks represent the relevant structures within the enterprise, typically business, applications, information, technology and their individual relationships to business performance. EA enables a comprehensive approach to the architectures, including their relationships, which constitute an enterprise (Prado, 2009). EA is the glue that integrates each of these architectures into a cohesive framework where business activities use information that must be collected, organized and distributed using applications that run on technology such as computers and networks (Figure 1).

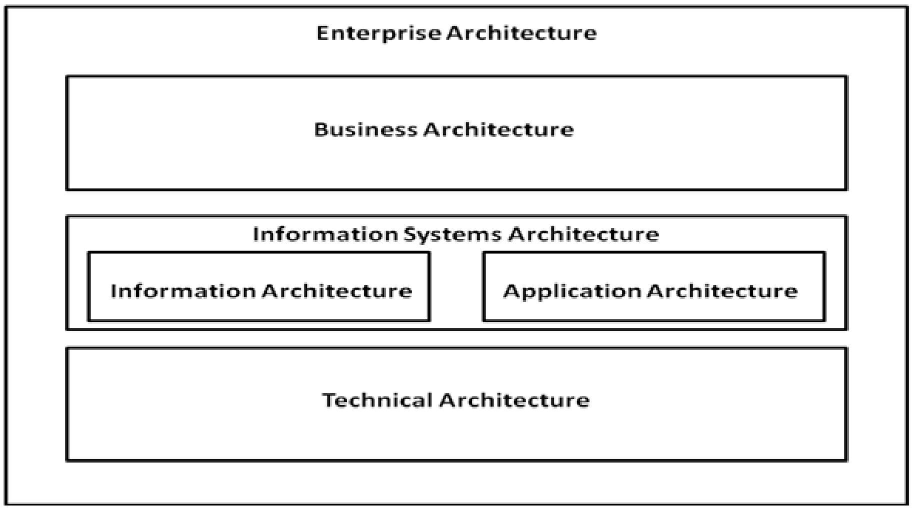

Figure 1: The different architectures in the framework of Enterprise Architecture.

The Business Architecture is the result of defining the business strategies, processes, and functional requirements using adequate methods and models. It's the base for identifying the requirements for an Information System, which support the business process. The Information Architecture describes the data used by the business. It's the result of modeling the information that is needed to support the business processes and how the data is processed. The Application Architecture provides a framework focused on developing and implementing applications to fulfill the business requirements. These two architectures merge to a Information Systems Architecture. The Technical Architecture provides the foundation that supports the applications, information and business processes identified in the other three architectural layers (Pereira & Sousa, 2004). Although all of these architectures compose the Enterprise Architecture, in this paper we will propose the first step for an EA-approach for supporting delivery scheduling of biofuels in Sweden.

A successful Information Systems starts with an understanding of the business processes of an organization and the first step in development of an Information System is documenting the business process according to the particular viewpoint and purpose. Business process-models are mainly used to learn about the process, to make decisions on the process or to develop business process software. Aguilar-Savén (2002) presents a framework for classifying business process-models according to their viewpoints and purposes. An IDEF0-model is a structural graphical representation of the activities performed presenting the input, control, output and mechanism associated with each activity (Figure 2). The process can be further decomposed to show lower-level activities (Aguilar-Savén 2002, Kim & Jang 2002).

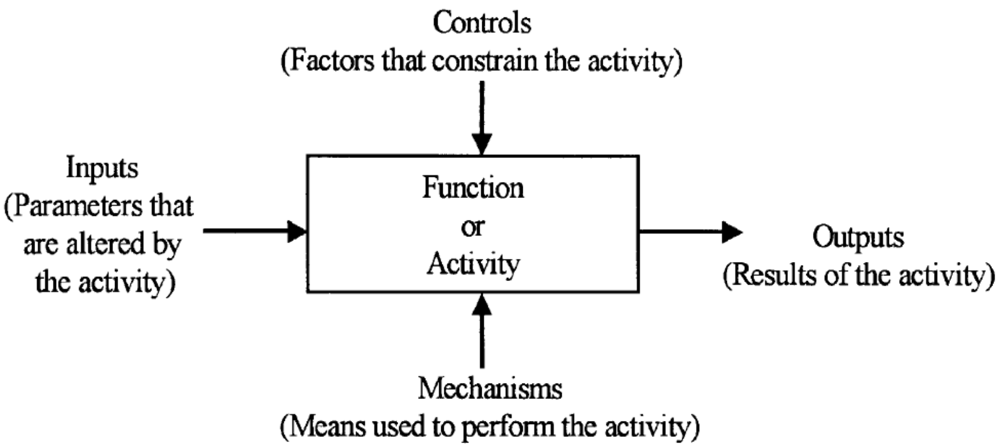

Figure 2: Basic IDEF0 syntax for process modelling (Kim & Jang, 2002)

A Create-Read-Update-Delete (CRUD) matrix is one popular approach to modelling data and process interactions. The matrix is a graphical representation of the EA, containing the relationship between the business processes and the data they use. The CRUD matrix is a tool to identify the relationship between each activity and their corresponding processing of information (C=Create, R= Read, U=Update, D=Delete) within delivery scheduling for a typical supplier and customer respectively. Certain processes will create data and others may read the data, while still other processes could update that data. The matrix identifies the integration bridges in the EA through the data processed in delivery scheduling. When all the necessary relationships are recorded, the matrix illustrates patterns in the way data are processed throughout the business process (Guerra et al., 2005).

Goals - The goal of this study is to clarify

a) the generic sequence of activities performed within the delivery scheduling of biofuels
b) and the information needed to support the execution of these activities.

The process will be presented in an IDEF0-model from both supplier and customer perspective.

MATERIALS AND METHODS

Both suppliers and customers are included in the study since information essential for the process Delivery Scheduling is exchanged between supplier and customer. The total number of respondents was 11 with 5 suppliers and 6 customers (Table 1). The suppliers were grouped in classes of delivered quantity of biofuels (boundary of 3 TWh). The customers were grouped in classes of inventory cover time (boundary of 7 days of supply).

Table 1: Number of respondents per respondent group in the study

	Supplier		Customer	
Respondent group	Small (< 3 TWh)	Large (>3 Twh)	Shorter inventory cover time (< 7 days supply)	Longer inventory cover time (> 7 days supply)
No. of respondents	3	2	3	3

The study was divided in to two stages; personal (qualitative) interviews and following telephone interviews. The personal interviews were designed to capture the activities performed within the process of Delivery Scheduling. The following telephone interview was developed based on the personal interview and was focused on capturing the information processed by the activities.

RESULTS

It was found that delivery scheduling was comprised of 4 sub processes for a typical supplier and customer respectively. The sub processes for a supplier in the IDEF0-model (Figure 3) were Create annual prognosis (A1), Contract quantity with customer (A2), Plan monthly supply of biofuels(A3) and Deliver (A4). These sub processes were comprised of over 30 individual activities performed by production and transport managers. The sub processes Create annual prognosis (A1) and Contract quantity with supplier (A2) were performed on a seasonal basis in order to make a prognosis for the supply of biofuels in certain time intervals during the season and to distribute the biofuels through a contract established with the customer. The sub process Plan monthly supply of biofuels (A3) for the deliveries was created every month, but with a planning horizon regarding rest of the season. The sub process Deliver (A4) was executed every week after a Call-off for biofuels is received from the customers.

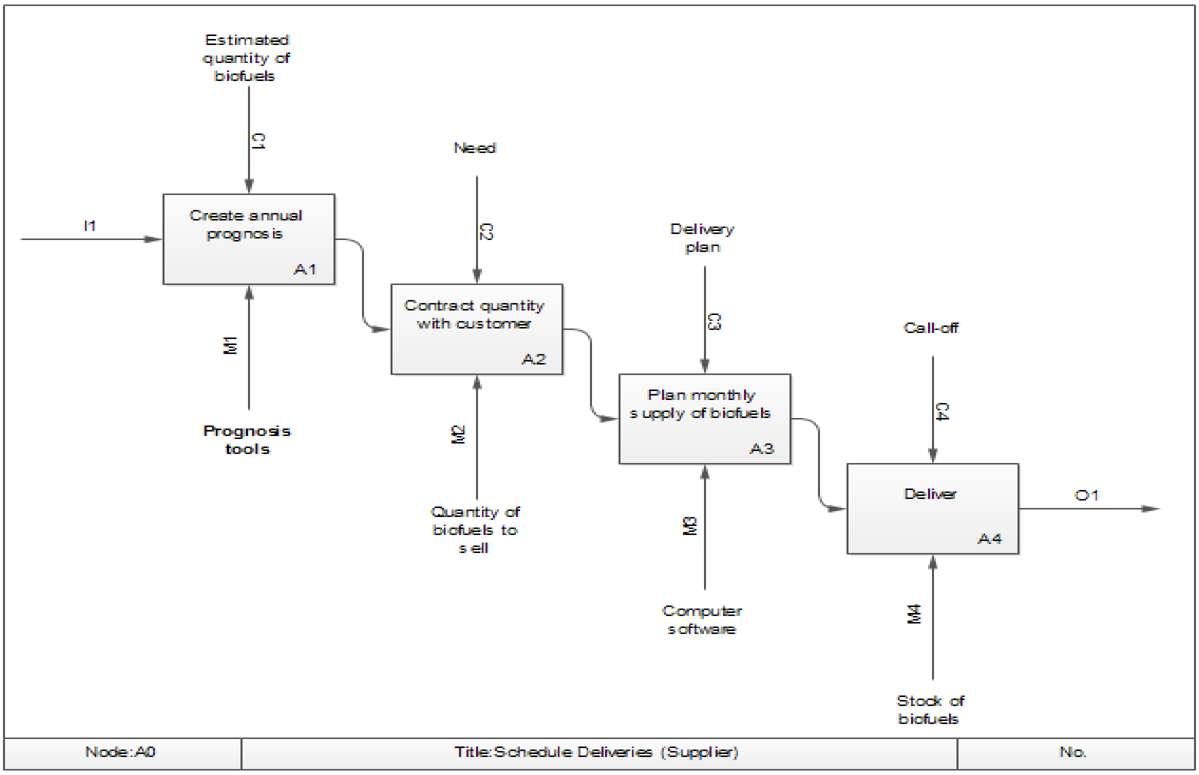

Figure 3: The 4 sub processes within delivery scheduling for a typical biofuel supplier.

The IDEF0-model for a customer with longer inventory cover time (> 7 days of supply) consists of the sub processes Create annual prognosis (A1), Contract quantity with supplier (A2), Plan monthly orders (A3) and Call-off (A4) comprised of close to 30 activities. The first two sub processes was performed on a seasonal basis, but the following, Plan monthly orders (A3) and Call-off (A4), was performed on a monthly and on a weekly basis respectively (Figure 4). Create annual prognosis (A1) and Contract quantity with customer (A2) is performed in order to plan the demand of biofuels and to establish a contract with the supplier for a yearly quantity of biofuels specified in to time intervals through an enclosed Delivery plan. The sub process Plan monthly orders (A3) is performed in order to plan the sub processes Call-off (A4) for the following month.

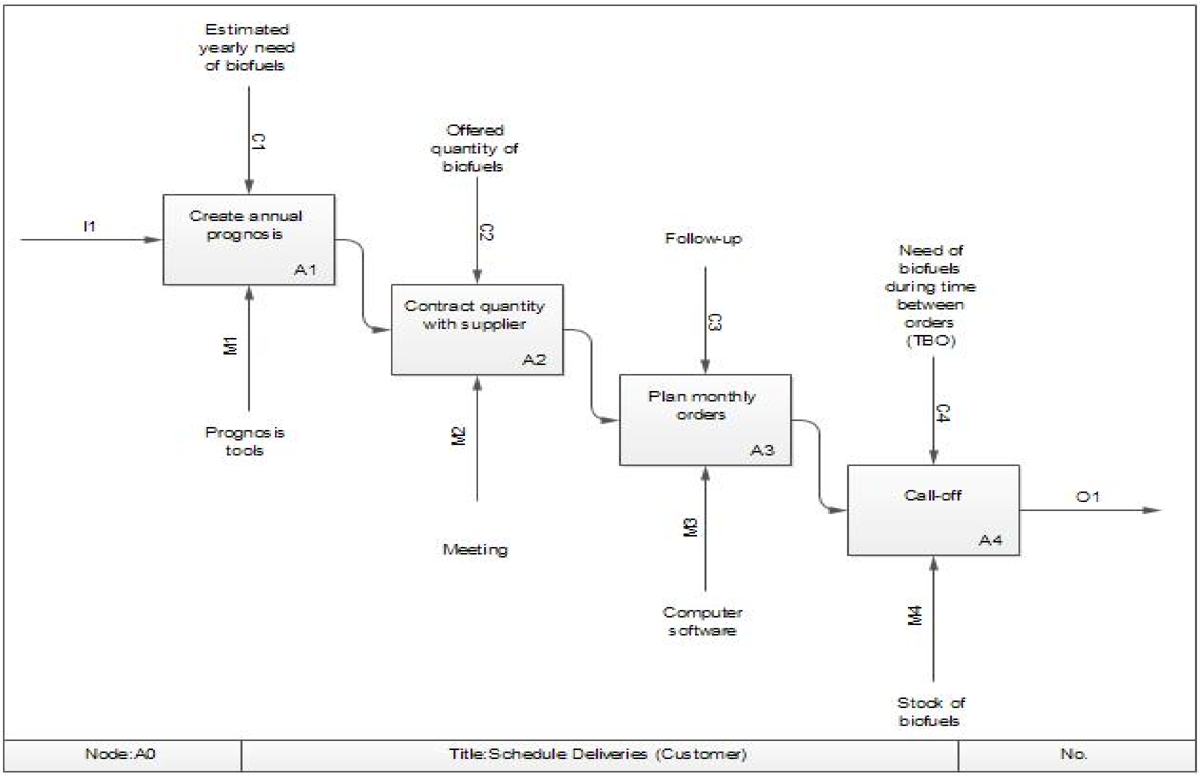

Figure 4: The 4 sub processes within delivery scheduling for a typical biofuel customer with a longer inventory cover time (> 7 days of supply).

The IDEF0-model for a customer with a shorter inventory cover time (< 7 days of supply) consists of 4 sub processes (Figure 5). The two IDEF0-models for customers are quite similar, but deviate in the third sub process where a customer with a shorter inventory cover time performs Follow-up (A3). The sub process Follow-up (A3) is performed in order to create a base for planning the orders, which is planned and placed every week in the sub process Call-off (A4). Customers with a longer inventory cover time plans the orders in the sub process Plan monthly orders (A3) and place them in the sub process Call-off (A4).

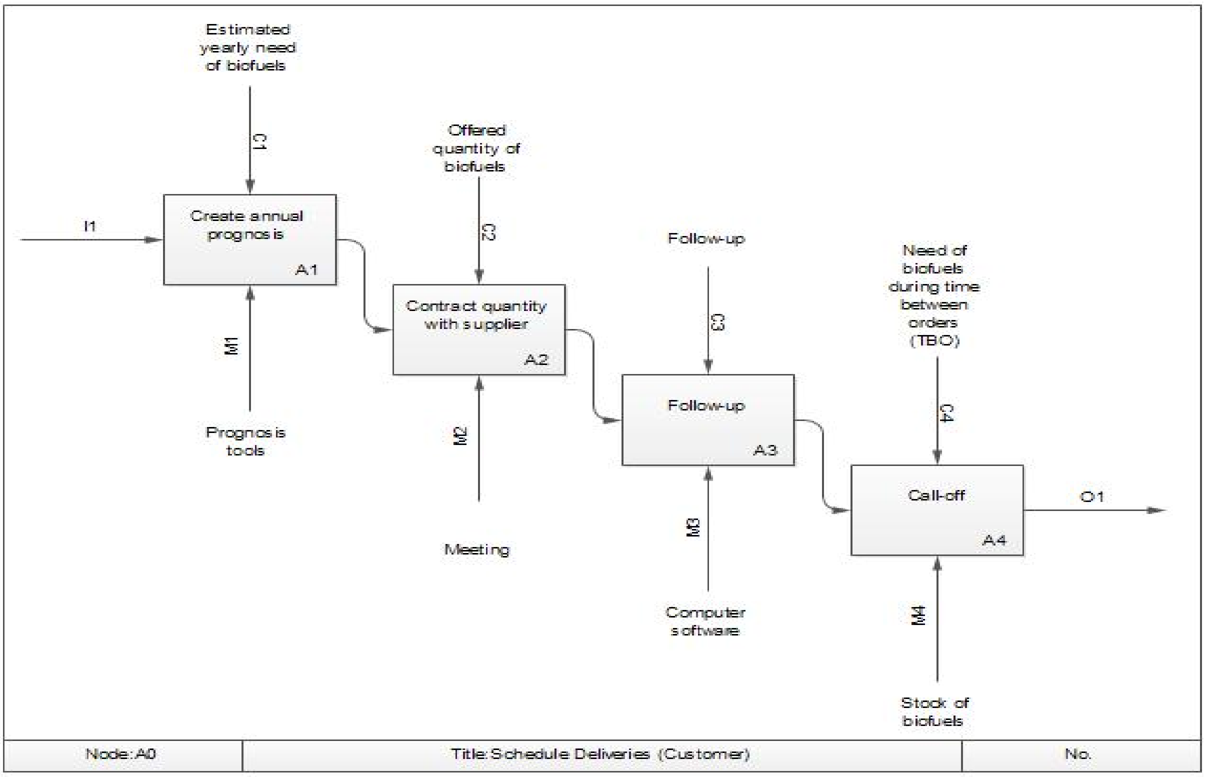

Figure 5: The 4 sub processes within delivery scheduling for a typical biofuel customer with a shorter inventory cover time (< 7 days of supply).

Information processing (CRUD) matrices

The CRUD matrices showing information processing model the processes at a greater level of detail (activities) than the earlier results (sub processes in figures 3, 4 and 5). The CRUD matrices show that similar activities, in particular activities related to follow-up, are performed by both supplier and customer respectively (Tables 2, 3 and 4). Activities related to follow-up are performed with the purpose of creating a base for decisions made in the Delivery Scheduling process. This is made through comparing the results from the sub process Deliver (A4) and Call-off respectively (A4) with the norm i.e. the Delivery plan. When the results don't match the Delivery plan, this is taken in consideration in the following sub processes Deliver (A4) and Call-off (A4) in order to match the Delivery plan.

Activities executed by customers in different groups (Table 1) deviate with respect to frequency of occurrence. The activity Plan the demand of biofuels is an activity, included in the sub process Plan monthly orders (A3), executed on a monthly basis for a customer with a longer inventory cover time. The identical activity is executed on a weekly basis for a customer with a shorter inventory cover time, included in the sub process Call-off (A4). The information used in similar activities is to a high degree, but not fully corresponding. The usage of information varies in a few activities which the CRUD matrices confirm, activities such as Call-off (A4).

Table 2: Information processing (C=Create, R= Read, U=Update, D=Delete) within delivery scheduling activities for a typical supplier

Activity \ Information	Key performance indicator (Wh/truck)	Order	Delivery report	Production plan of biofuels	Follow-up contract	Delivery plan	Supply of biofuels
A2.3 Create contract with Delivery plan				CR		CR	R
A2.5 Follow-up contract		R	R		R	R	
A3.1 Plan production of biofuels				R		R	R
A3.3.1 Follow-up Production plan				RU		R	R
A3.3.2 Follow-up Deliveries	CU	R	R				
A3.3.3 Follow-up Delivery plan		R	R		C	R	
A4.1 Receive Call-off		CU					
A4.2.1 Internal inform of Call-off		R					
A4.2.2 Plan delivery	R	R		R			R
A4.2.3 Order transport		R					
A4.3 Follow-up Call-off		R	R				

Table3: Information processing (C=Create, R= Read, U=Update, D=Delete) within delivery scheduling activities for a typical customer with a longer inventory cover time (> 7 days of supply)

Activity \ Information	Follow-up supplier	Price of biofuels (average)	Follow-up moisture content (%)	Production plan of heat	Price of biofuels (specific supplier)	Supply of biofuels	Key performance indicator (Wh/truck)	Call-off	Delivery report	Monthly quota of energy in Delivery plan
A2.3 Create contract with Delivery plan		CU		R	C					CU
A2.4 Follow-up contract	R								R	R
A3.1.1 Estimate heat production				R						
A3.1.2 Estimate consumption of biofuels				R						
A3.1.3 Manage supply of biofuels				R		R				
A3.1.4 Plan the demand of biofuels				R		R				
A3.2.1 Follow-up supply		R				CU				
A3.2.2 Follow-up supplier	CU		CU				CU	R	R	R
A3.2.3 Follow-up cost of biofuels		R							R	
A3.2.4 Follow-up Delivery plan								R	R	R
A4.1.1 Allot supplier share of total need	R		R							R
A4.1.2 Convert energy (Wh) to loads (trucks)							R			
A4.1.3 Call-off	R			R				C		R
A4.1.4 Internal inform of Call-off								R		
A4.2 Follow-up Call-off						R		R	C	R

Table 4: Information processing (C=Create, R= Read, U=Update, D=Delete) within delivery scheduling activities for a typical customer with a shorter inventory cover time (7< days of supply)

Activity \ Information	Follow-up supplier	Price of biofuels (average)	Follow-up moisture content (%)	Price of biofuels (specific supplier)	Estimated temperatur for time between orders	Supply of biofuels	Key performance indicator (Wh/truck)	Call-off	Delivery report	Monthly quota of energy in Delivery plan
A2.3 Create contract and Delivery plan		CU		C						CU
A2.4 Follow-up contract	R							R	R	R
A3.1 Follow-up supply of biofuels		R				CU				
A3.2 Follow-up supplier	CU		CU				CU	R	R	R
A3.3 Follow-up cost of biofuels				R					R	
A3.4 Follow-up Delivery plan								R	R	R
A4.1.1 Estimate heat production					CR					
A4.1.2 Estimate consumption of biofuels					R					
A4.1.3 Manage stock					R	R				
A4.1.4 Plan the demand of biofuels					R	R				
A4.2.1 Allot supplier share of total need	R		R							R
A4.2.2 Convert energy (Wh) to loads (trucks)							R			
A4.2.3 Call-off	R		R		R			CU		R
A4.2.4 Internal inform of Call-off								R		
A4.3 Follow-up Call-off					R	R		R	C	R

DISCUSSION

IDEF0 is a model best suited to use in an EA-approach. Other models exist, but they are less or poorly suited to process modeling for the purpose of Information System design. The results identify the activities within delivery scheduling through a qualitative study but they have not been tested with statistical methods in a quantitative study. However, the data collected varied little within respondent groups which supports the development of a generic model for delivery scheduling of biofuels in Sweden. This study is the first step in an EA-approach and further work is needed (such as Entity Relationship diagrams) to give a cohesive description of the architectures needed to support delivery scheduling.

CONCLUSIONS

The results of this study show that identical activities are performed by both the supplier and the customer respectively. A deviation in frequency of occurrence is observed for customers. A customer with shorter inventory cover time plans the demand for biofuels every week, whereas a customer with longer inventory cover plans the demand for biofuels on a monthly basis. It is important to note that the information used in the completion of some activities varies, which can lead to decisions based on very different principles.

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AIR QUALITY ON BIOMASS HARVESTING OPERATIONS

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ABSTRACT

The working environment around logging operations can be very dusty. But, air quality around logging operations is not well documented. Equipment movements and trafficking on the landing can cause dust to rise into the air. The addition of a biomass chipper creates different air flow patterns and may stir up additional dust. This project addresses two topics related to air quality on biomass harvesting operations.

The first topic addresses the quantity of dust in the air during biomass harvesting operations related to human health. Wood and other dusts can cause eye irritation, and in severe cases, may scratch the cornea. Exposure to wood dust may also cause allergic respiratory reactions, especially in people who suffer from asthma. During this study, the measure of particulate matter in the air is compared to the OSHA standards for nuisance dust (particulates not otherwise regulated) in a working environment.

The second topic addresses the impact of air quality on biomass feedstock characteristics. Analysis quantifies the amount of dust in the air and estimates the impact that it could have on the amount of ash in biomass. The research goal of the overall project is to provide a thorough analysis of air quality on landings of various biomass harvesting operations to determine the potential impacts of nuisance dust on human health and biomass feedstock quality. This paper documents findings from an initial project installation in Alabama.

Keywords: biomass harvesting, air quality, air sampling, biomass ash content, human health

INTRODUCTION

It is widely accepted that logging operations are a dusty work environment. This is clearly evident from accumulated dust in cabs and on machine surfaces. However, air quality on biomass harvesting operations is not well understood, nor documented in existing literature. A variety of activities occur on the landing and each may contribute to poor air quality.

Soil type and moisture content may impact air quality and ash content in processed biomass. When soil moisture content is high, fewer particles may become airborne as a result of equipment movements. Particle sizes associated with different soil types may impact the amount of dust that becomes airborne. Soils with smaller particles, <0.1 mm diameter, that rise more than 30 cm into the air may stay suspended for longer periods than larger particles (White 2006). Larger particles (>0.1 mm) do not usually rise over 30 cm, and usually fall back to the ground.

The impact of dust concentrations on air quality of the work environment of forest workers on biomass harvesting operations is unknown. Although personal exposure to dust can be measured, it may be highly variable due to differences in operational characteristics between logging sites, site differences, and a host of other variables. Dust concentration measurements on biomass harvesting operations are needed to quantify air quality and determine the impact that it may have on the health of forest workers.

Chippers and grinders may change the air flow on a landing, and the volume of air flow varies between machines. In a dusty working environment, dust will also be present in the air flow and may get deposited on processed biomass. The impact of dust concentrations on biomass feedstock qualities is also not documented in existing literature.

This introduction provides a brief summary of air quality as it relates to the working environment and human health. It also examines the potential impact of air quality on biomass feedstock quality.

Human Health

Standards for air quality in the working environment are regulated by the United States Department of Labor, Occupational Safety and Health Administration (OSHA). The Occupational Safety and Health Administration (OSHA) was created to ensure safe and healthful working conditions for working men and women by setting and enforcing standards and by providing training, outreach, education and assistance. ‘"Standard" means a standard which requires conditions, or the adoption or use of one or more practices, means, methods, operations, or processes, reasonably necessary or appropriate to provide safe or healthful employment and places of employment’ (OSHA 2011). As such, air quality standards are addressed by OSHA (1910.1000, Air Contaminants). OSHA sets enforceable permissible exposure limits (PELs) to protect workers against the health effects of exposure to hazardous substances. PELs are regulatory limits on the amount or concentration of a substance in the air. Forestry does not have any industry-specific PELs, however some other industries do. The general air quality standards for all inert or nuisance dusts (whether mineral, inorganic, or organic) not listed specifically by substance name are covered by the limits set for Particulates Not Otherwise Regulated (PNOR). The limits for PNOR are 15 mg/m^3 for total dust, and 5 mg/m^3 for the respirable fraction (OSHA 2011).

There are health issues related to nuisance dust in the working environment. Potential symptoms from exposure to nuisance dust include irritation to skin, throat, or upper respiratory systems. Dust may also cause irritation to the eye, and in severe cases, may scratch the cornea. Exposure to wood or inorganic dusts may also cause allergic respiratory reactions, especially in people who suffer from asthma. However, not all dusts pose the same level of health hazards. OSHA (2011) lists the following factors that can make inorganic dust particles harmful:

- Dust composition
    - Chemical
    - Mineralogical
- Dust concentration
    - On a weight basis: milligrams of dust per cubic meter of air (mg/m3)

    - On a quantity basis: million particles per cubic foot of air (mppcf)
- Particle size and shape
    - The particulate size distribution within the respirable range
    - Fibrous or spherical
- Exposure time

Forest workers on biomass harvesting operations can be exposed to nuisance dust in many ways. On a whole tree chipping operation, most workers operate in enclosed machine cabs. Windows and doors are often opened during normal operations. One of the primary reasons to open doors or windows is to communicate with other workers on the job site. These communications are considered administrative delays in productive environments, so operators do not allow the 'dust to settle' prior to opening a window or door. Modern equipment cabs have a positive pressure which keeps dust out, but open windows bypass the machine's cab air filtration system and may negatively impact the interior air quality.

Truck drivers are also in the landing area during active operations and exposed to nuisance dust. If a chip van has an open top, the truck driver often exits the truck's cab to watch the operation and move the truck/trailer forward to achieve a full payload. If the chip van is loaded from the rear, chips are 'blown' in and fine airborne particles exit the trailer through screened openings in the van. Nuisance dust that becomes airborne due to machine activity near the chipping operation may affect the work environment for truck drivers.

Many of the other workers on biomass harvesting operations are exposed to nuisance dust. Measurements of dust concentrations are needed on a variety of biomass operations.

Ash Content/Biomass Quality

Inorganic elements in wood are often referred to as ash content in biomass. Some of these elements occur naturally in trees because they are brought into the tree from the soil through the root system and sap stream (Koch 1972). In processed biomass, inorganic soil particles that adhere to the tree are included in ash content.

Ash generally constitutes less than 0.5 percent of oven-dry loblolly (Pinus taeda) or longleaf pine (Pinus palustris) stemwood (Koch 1972). Needles of loblolly pine have been found to have an ash content of 2 percent (Metz and Wells 1965). Although this amount seems very small, it results in a residue after energy conversion processes. When biomass is burned in a boiler, everything that doesn't completely combust can fuse together. This non-combusted material includes impurities, such as metal, sand and plastic; and the inorganic substances from biomass. This fused material can block the burning ports in a boiler so that the boiler doesn't heat evenly or efficiently. Ash content is also very important when pelletizing woody biomass. The ash in biomass can cause wear on pellet die, reducing die life. In addition, residential pellet customers want premium pellets with low ash content to reduce the maintenance of removing ash from their wood stoves.

Ash content is often measured through destructive analysis by grinding the material very finely, then drying it in a muffle furnace (ASTM D-1102 2007). In the furnace, the organic material in the biomass burns off and the inorganic components are left in the bottom of the crucible. Ash content is usually reported as a percentage of the oven-dry weight of wood. The resultant ash can be further analyzed for mineral content.

In 2006, pulp mills in Alabama were beginning to add limits to the ash content in their biomass delivery specifications (Mitchell 2006). Later, in 2008, biomass deliveries from land clearing operations were blocked from a mill using biomass as boiler fuel due to the high levels of ash in the material. The land clearing operation included pulling the stumps and grinding them along with other biomass material from a land clearing operation. Samples from this land clearing operation were found to contain an ash content range of 1 to 36 percent (Mitchell unpublished data). In another study, a front-end loader was used to feed biomass into a tub grinder and resulted in high ash percentages ranging from 20 to 65 percent (Rummer unpublished data). In these examples, equipment selection impacted the ash content in processed biomass.

Other sources of inorganic elements (ash) may occur as a result of the harvesting system. A variety of research is currently being conducted in the Research Work Unit to quantify the impacts of harvesting on feedstock characteristics. Researchers are studying whether the process of skidding whole trees from the stump to the landing increases the ash content in processed whole-tree biomass as opposed to trees that were forwarded or fully suspended during the extraction phase of harvesting. Another research topic related to ash content is quantifying the amount of ash in bark, stemwood, limbs and needles of sampled trees. These topics and more can provide information that can lead to improved harvesting techniques to increase the quality of biomass by reducing the ash content.

In this project, nuisance dust will be examined. Specifically, this project will address safety issues (human health) related to air quality on landings of biomass harvesting operations. These dust measurements will be compared to the OSHA standards to determine whether they are within the defined PEL. It will also analyze the impact of air quality on processed biomass by measuring ash content, which may negatively affect the value of the forest product. The results from a short, introductory field study are reported in this paper to share the methodology and initial findings from the study.

SITE LOCATION/LOGGING OPERATION

Data were collected for two days on a logging operation in Butler County, Alabama. Equipment on the landing consisted of a Precision Husky WTC-2366 used in combination with a ForestPro flail. A TigerCat 240 tracked loader fed the flail machine and removed residues from between the flail and the chipper. A rubber-tired HydroAx 411E with a brush blade was used to pile flail and chipper rejects at the edge of the cleared landing. The study was installed in April, 2011.

Although the study was planned for installation on a biomass harvesting operation, this paper summarizes data from a clean chipping operation. The observed logging operation usually processes biomass, but current markets and production-limiting quotas required that the logging business owner purchase a flail and swap between clean chipping and biomass processing as markets dictate. Data from this clean chipping operation may prove to be advantageous by providing a comparison point between clean and dirty chip processing.

METHODOLOGY

An air sampler was used to measure the volume of particulate matter (mg m^{-3}) in the working environment during active chipping operations. One air sample was collected for each load, resulting in one observation per load of chips. The sampler was located close to the chipper in order to get a base line, or worst case, measurement. Exposure time for individual workers was not collected in this initial study installation.

Methodology outlined in NIOSH (2003) was followed for determining total dust using an Airchek model 224-PCXR7 air sampling system. Sampling was performed during the processing of nine loads of chips from a single clean chipping operation.

Airborne particles were collected in cartridges attached to an Airchek model 224-PCXR7 sampler. Each cartridge contained a polyvinyl chloride (PVC) filter (37 mm diameter, 5.0µm pore size) and was sealed to protect against external contamination. Filters were exposed on the sampler for the duration of time that it took to process one load of chips. Once an observation was completed, the sample cartridge was sealed (plugged) and stored upright in a cooler for transport to the laboratory.

Sampler airflow was measured and calibrated at the beginning and end of every observation using a Bios DryCal primary flow meter air calibrator. Any air flow differences in the calibration readings between the start and end of each observation were used for corrections. Due to the filter's sensitivity to oils and dust, some prepared cartridges were exposed on the landing to quantify any handling and storage of the prepared cartridges that could have impacted the results of the observations. These blank cartridges were used to determine if a correction factor was needed for the filter weights.

Soil moisture content testing followed the methods outlined for standard bulk density testing methods (Grossman and Reinsch 2002). A soil sample was collected during each air sampling observation. Core soil samples were collected by driving 50 mm diameter metal corers into the soil. The samples were cut to 25 mm depth, labeled, sealed and stored in a cooler for transportation to the laboratory. The samples were cut to only include the top 25 mm depth of soil to better characterize the soil moisture on the soil surface. Samples were dried at 105^{o}C for 24 hours, then reweighed. Soil type information was obtained using USGS soil maps.

Wood chips were collected to determine if there were any relationships between dust concentration, soil moisture content, and ash content in processed chips. Samples were collected in accordance with laboratory analysis procedures outlined by the National Renewable Energy Lab (Sluiter 2005). Chip moisture content was determined using methodology described in ASTM (2006) standard E-871 (standard test method for moisture analysis of particulate wood fuels). Ash content of the wood chip samples was determined using ASTM standard D-1102 (standard test method for ash in wood).

RESULTS AND DISCUSSION

The basic descriptive statistics shown in Table 1 were calculated from the limited initial data collected. The current dataset was limited to nine observations because of the small tract size and limited delivery quota during the first study period.

Table 1. Descriptive Statistics

	N	Mean	Standard Deviation
Biomass ash content (%)	8	0.305	0.146
Biomass moisture content (%)	9	56.9	2.4
Soil moisture (%)	9	19.4	2.2
PNOR-area (mg/m^3)	8	1.3	1.34

Air Quality

Exposure levels of the 9 air quality samples ranged in value from 0 to 11 mg m^{-3}. The exposure level measured for load 5 was higher than the rest, and may be attributed to a blown hydraulic hose that sprayed fluid onto the air sampler. Removal of load 5 from the analysis resulted in an average exposure level of 1.3 mg m^{-3} for the remaining 8 observations, as shown in Table 1. These remaining 8 observations had exposure levels ranging from 0 to 4 mg m^{-3} (95 percent CI = 0.264 to 2.329 mg m^{-3}). Exposure levels measured during this initial test are well within the PEL of 15 mg m^{-3} (OSHA 2011) for a working area, or less than 1 percent of allowable PNOR. Accuracy of these exposure levels could be increased in the future by using a 5-place balance as opposed to the 4-place balance used in this initial testing.

Temperatures during the study ranged from 21 to 24 ^{0}C (70 to 76 ^{0}F). Relative humidity ranged from 40 to 73 percent. Relative humidity is usually low (<70 percent) during dust storms (Hagen and Woodruff 1973), therefore it is expected that dust levels would have been low during the initial field study.

Ash

The mean ash content analysis for 8 samples of clean chips (chip samples were not collected for load 5) was 0.31percent (95 percent CI = 24.7 – 36.2 percent). Low ash content was expected since the chips were processed through a flail prior to chipping (minimal bark and needles).

Since this initial field study includes only limited data, and was collected on a clean chipping operation, a simple analysis was performed to determine how much dust concentration would be necessary to impact the ash content in a load of biomass chips. An assumption of this analysis is that the total dust on the sampling filter is inorganic and considered ash. During the initial data collection, processing times ranged from 39 to 81 minutes with an average time of 52 minutes.

Therefore, the analysis includes a variety of processing times. Longer observation times may impact the amount of dust particles captured on the sampling filters.

The sensitivity analysis began by considering three levels of ash content acceptable in the delivered load. Pellet mills are sensitive to ash, so the lower limit for the analysis was set at 2 percent. Additional amounts of 5 and 10 percent ash were also included. Assumptions necessary for the analysis were that a load of biomass weighed 23.6 tonnes (26 tons) and contained 50 percent moisture. Ash is calculated on a dry biomass basis. At 2 percent ash, the load would contain 236 kg (520 lbs.) of ash. At 5 and 10 percent, the ash in a load would be 590 kg. (1,300 lbs.) and 179 kg. (2,600 lbs.), respectively. The Precision Husky WTC-2366 has an air flow rate of 311.485 m^3 min^{-1} (11,000 ft^3 min^{-1}) and at various loading time periods, different total volumes of air would be blown through the chipper. Table 2 displays the dust concentrations that would have to be sampled in order to reach various ash concentrations from accumulated total dust in the working environment, and without consideration of the ash in and on the biomass.

Table 2. Total accumulated ash (percent) based on dust concentrations and loading times

Dust Concentration (mg m^{-3})	**Processing Time**					
	15	**30**	**45**	**60**	**75**	**90**
2	0.0	0.0	0.0	0.0	0.0	0.0
15	0.0	0.0	0.0	0.0	0.0	0.0
17000	0.7	1.3	**2.0**	2.7	3.4	4.0
42000	1.7	3.3	**5.0**	6.7	8.3	10.0
84000	3.3	6.7	**10.0**	13.3	16.6	20.0

Longer loading times may contribute to higher ash contents solely based on the dust concentration in the working environment and the volume of air moved. However, the PEL for total dust concentration (OSHA 2011) is much lower than would be required to attribute 2 percent of ash content to nuisance dust. Based on this analysis, a load of chips should not have any discernable ash content due to dust in the working environment.

Soil

The soil type on this first test site was Luverne, sandy loam, on 5-8 percent slopes. This is a well drained soil type. Sandy loam soil types usually contain more sand than clay or silt. Sand particles are larger than clay or silt and could possibly explain the lack of ash collected on the air sampling filters.

Approximately 3.8 cm (1.5-inches) of rain fell on the test site the day before data collection began. Rainfall data were estimated using NOAA rainfall maps and the nearest weather station data. The Luverne soil type is characterized as being well-drained, and there was no standing water present on the site during chipping operations. The landing area had been cleared a week earlier in preparation of moving onto the site during the morning of the first day of data collection. Laboratory testing revealed that the average soil moisture on the site during data collection was fairly low, 19.4 percent. However, when equipment trafficked in the landing area, there were no visible signs of soil lifting into the air. One would expect clouds of dry matter to rise into the air with such low soil moisture. This may be partially explained by the type of chipping operation. Flail residues coupled with the chipper overs and unders created a layer of material that formed a mat on the operational area of the landing. This mat may have reduced the aerial soil dispersion.

SUMMARY

Analysis during somewhat favorable conditions had levels that were less than one percent of allowable nuisance dust for a working area. Future studies on a variety of soil types may indicate whether soil particle size has an impact on the air quality on biomass chipping operations. The mat of residues on the landing of this clean chipping operation may have helped the air quality on this study site by limiting airborne particles. Further testing on a variety of sites should also provide further insight into the relationship between soil type and biomass ash content.

Dust in the air sampler filters could be further analyzed using an ash test. This test would determine whether the source of the nuisance dust was organic or inorganic. The inorganic component would be considered an impurity in the biomass, whereas the organic component could include wood dust and other particles that would not negatively impact the quality of the biomass produced.

The results of this analysis of air quality on biomass chipping operations are expected to be useful to land managers, loggers, and the biomass industry. Land managers could use the results of this study to determine whether dust abatement techniques would be warranted on their land during logging operations. Loggers, and their employees, could benefit by understanding the health exposure risks associated with biomass chipping operations. The biomass industry could benefit from the knowledge gained about the impact of air quality (nuisance dust) on biomass feedstock quality.

Further analysis is needed to fully address the objectives of this study. This study will be replicated on other sites and further investigate the variables that are determined to be significant to human health or biomass quality. Additional information regarding the biomass source (whole tree, delimbed/debarked, residues-only), species, and chipper type will be documented for each field investigation.

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Harvesting Small Trees for Bio-Energy

John Klepac, Bob Rummer, and Jason Thompson[1]

ABSTRACT: A conventional whole-tree logging operation consisting of 4-wheeled and 3-wheeled saw-head feller-bunchers, two grapple skidders and a chipper that produces dirty chips was monitored across several stands and machine performance evaluated. Stands were inventoried to determine density, volume, and basal area per acre and will be used to relate machine performance to stand characteristics. Costs per hour and per ton will be calculated for each function and a total system cost will be determined for the conventional system. These costs will be used to compare the conventional system to a newly designed system for harvesting trees for bio-energy.

Keywords: harvesting, biomass, bio-energy, productivity.

INTRODUCTION

The US consumes more fossil fuel than any other country and most (51%) of these petroleum products are imported (U.S. EIA, 2011). The federal government has focused R&D and policy initiatives to address the growing dependence on foreign oil and the reliance on finite fossil energy supplies. In 2009 the Department of Energy offered a funding opportunity (DE-FOA-0000060) requesting proposals to develop supply systems that could handle and deliver high volumes of renewable biomass. The overall objective of this program is to stimulate the development and commercial deployment of systems for harvest, collection and processing that will support the rapid expansion of a liquid biofuels industry. Five proposals were selected, three working on systems for agricultural and perennial crops and two addressing woody biomass. A consortia organized by SUNY College of Environmental Science and Forestry, Syracuse NY is working on developing improved short rotation willow systems. Another team led by Auburn University is funded to develop a woody biomass system around intensive southern pine management. Development of a new harvesting system requires benchmarking of current technology to serve as a reference for any improvements attributed to the new technology. This report describes benchmarking evaluations for the pine feedstock project.

The Auburn University High Tonnage project is built around the assumption that a likely feedstock for energy production in the US South would be intensively grown pine. Loblolly pine can achieve yields of 22.4 Mg ha^{-1} yr^{-1} (Munsell and Fox 2010). Assuming a 15-yr rotation, 90M tonnes (green) could be sustainably produced each year from a total of about 4M ha dedicated to intensive pine management. The new mechanized harvesting system (Rummer et al. 2010) will be optimized for this type of stand. Trees would be relatively uniform (diameter and height) and closely spaced.

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The first phase of the project included evaluation of the cost and performance of currently available equipment. Typical southern pine harvesting systems employ wheeled feller-bunchers with sawheads and grapple skidders to move wood to roadside. When biomass is recovered as part of southern pine harvesting a roadside chipper may be added to turn small material into fuel chips before trucking. Clean chips can be produced by the addition of a flail debarker to the system.

This paper discusses methods used to evaluate current harvesting systems operating in small-diameter stands and presents productivity results for felling and skidding components, in addition to stand conditions of the study sites.

METHODS

Operation

In May 2010 personnel from the Forest Operations Research Unit in Auburn, Alabama began monitoring two biomass harvesting operations in south Alabama. One operation produced dirty chips while the other produced clean chips. Electronic activity recorders were placed in each machine on both operations to measure total productive machine hours spent on a site. Detailed time-and-motion studies were conducted on the dirty chip operation where felling and skidding functions were evaluated.

The two operations worked mainly in thinnings but occasionally performed clearcut prescriptions. For thinning prescriptions, a fifth row removal with thinning within the stand was performed. On the dirty chip operation, row removal, or corridor cutting, was mainly done with a Hydro-Ax 470[2] drive-to-tree feller-buncher with a circular saw head. Thinning within the stand was done with a Valmet 603 three-wheeled feller-buncher also equipped with a circular saw head. Bundles were built in the corridors by the Hydro-Ax and then skidded to the landing by a John Deere 648 and a CAT 525 grapple skidder. After bundles from a corridor were skidded, the Valmet 603 followed up by thinning within the stand. These bundles were also built in the corridors and then skidded. At the landing trees were feed into a Woodsman 334 chipper which blew the material into chip vans. Two clearcut stands were visited where one utilized the Valmet 603 while the Hydro-Ax was being repaired. The other clearcut stand utilized a Timber King drive-to-tree feller-buncher while the Hydro-Ax was working on a thinning operation.

Study Sites

To determine stand conditions where the equipment was working, fixed radius circular plots were installed on five sites. Either 0.04-ha or 0.02-ha plots were installed, depending on stand density. Within each plot, all trees from a 2.5-cm Dbh class and larger were measured for Dbh

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[2]The use of trade or firm names in this publication is for reader information and does not imply endorsement of any product or service by the U.S. Department of Agriculture or other organizations represented here.

and species recorded. Tree heights were measured on every 5th pine tree using a hypsometer. Hardwood tree heights were occularly estimated to the nearest 1.5 m on all hardwoods within a plot. Regression equations were developed (SAS, 1988) to predict total height as a function of Dbh for trees where total height was not measured. Total-tree green weights of pine trees 15.2 cm Dbh and smaller were calculated using equations developed by Phillips and McNab (1982). Weights for pine trees larger than 15.2 cm Dbh were estimated using appropriate regression equations (Clark and Saucier, 1990). Total-tree green weights of hardwoods were estimated using regression equations (Clark and others, 1985).

Post inventory assessments were completed on each thinned stand for determining percent removals. Rectangular plots 0.1-ha in size were installed in all except one stand where 0.04-ha plots were used. Plots were installed so that the two long sides were each centered in a cut corridor and ran parallel with the corridor. This insured both the corridors and stand area were appropriately represented in the plot.

Felling

Feller-bunchers were timed while performing clearcut, corridor and thinning cuts. When possible, Dbh was measured with calipers on trees to be felled and species recorded. A numbered card was attached to each measured tree. Total tree heights were estimated from regression equations developed from cruise data. Machines were recorded on video as they worked thru a study area and tree numbers were verbally recorded. Some sites were too dense for attaching numbered cards to trees and in these cases tree size and species were visually estimated and recorded. Elemental times of interest included move to first tree, accumulation, move-to-dump, and dump defined as follows:

Move to first tree began after trees in the head were dumped and the tires began rotating. The element ended when the saw reached the first tree.

Accumulation time began when the saw reached the first tree to cut and included all cutting and moving to each tree. Accumulation time ended after the last tree was cut and the tires started rotating for moving to dump.

Move-to-dump time included travel from the location of the last tree cut to the location where the feller-buncher was building bundles. The element began when the last tree was cut and tires started rotating and ended when the head started to tilt forward to dump.

Dump time was the time required to dump all trees in the head and started when the head began to tilt forward and ended when the head was empty and the tires started rotating to start moving to the first tree again.

Video tapes were time coded and analyzed using The Observer Video Pro software (Noldus Information Technology, 1997). Each time element was defined with a letter code and during viewing the appropriate code was entered at the end of each element to mark its termination.

Individual elements were summed to get total cycle time. Tree volumes for each cycle were calculated and summed to get total volume per cycle and tons per hour.

Skidding

To estimate skidder productivity variables of interest included cycle time, turn volume, and travel distances. Stopwatches were used to time cycle elements which included travel empty, position, grapple, intermediate travel, travel loaded, and ungrapple.

Travel empty time was the time required for the skidder to travel from the landing to the woods. The element started when the skidder ungrappled its load at the chipper and the tires began forward motion and ended at the point where the skidder stopped before backing up to grapple a bundle.

Position time included the time to back up to a bundle and started when the tires began reverse rotation and ended at the bundle when the tires stopped rotating.

Grapple time included the time required to secure a bundle in the grapple for transport to the landing. The element started when the tires when the tires stopped moving at the end of the position element and ended when the bundle was clamped in the grapple and forward motion started.

Intermediate travel included travel between bundles and occurred for cycles where the skidder grappled more than one bundle for transport. The element started after the previous bundle was grappled and the tires began forward motion and ended when the skidder reached the next bundle and rotation of the tires stopped.

Travel loaded time included traveling from the woods to the landing once a load was obtained in the grapple. The element started when grappling was complete and the tires began forward motion and ended at the chipper when forward motion stopped or when the grapple started to open.

Ungrapple time included placing skidded trees in a pile next to the chipper. The element began when either forward motion of the tires ended or when the grapple started to open and ended when the load was dropped.

Turn volumes were determined by measuring Dgl (Diameter at ground line) and sampling Dbh of trees within a bundle. Species of each tree was also recorded. Regression equations were developed to predict Dbh from Dgl for both pine and hardwood where Dbh was not accessible for measurement. The model to predict Dbh as a function of Dgl for pine had an R-square value of 0.94 and a C.V. (Coefficient of Variation) of 10.73 percent. The hardwood model had an R-square value of 0.87 with a C.V. of 13.52 percent. Total heights for both species were estimated from regression equations developed from the cruise information. The model to predict total height as a function of Dbh for pine had an R-square value of 0.66 with a C.V. of 16.71 percent.

The model to predict total height as a function of Dbh for hardwood had an R-square value of 0.68 with a C.V. of 28.98 percent. These variables were then used in appropriate regression equations to predict total-tree green weights of pine trees under 15.2 cm Dbh (Phillips and McNab, 1982), pine trees over 15.2 cm Dbh (Clark and Saucier, 1990), and hardwood trees (Clark and others, 1985). Travel empty, intermediate travel, and travel distances were measured with a distance wheel.

RESULTS

Study Sites

Detailed time study data were collected on six sites during the initial benchmarking phase; two clearcut sites and four thinning sites. Inventory data were collected on all sites except one clearcut. Mean Dbh of pine and hardwood combined among all five sites was 10.9 cm. Mean Dbh of pine and hardwood was 12.9 cm (n = 1561) and 6.9 cm (n = 758), respectively.

Stands ranged in initial stand density from 1699 trees ha^{-1} to 4202 trees ha^{-1} and ranged from 199 to 524 gt (green tonnes) ha^{-1} (Table 1). These stand conditions were assumed to bracket potential conditions in intensively grown energy plantations of the future. The prescription removed 66 percent of the trees and 57 percent of the volume for the thinned stands. Basal area reduction averaged 59 percent. Most of the trees were in the 5.1 and 10.2 cm classes (Figure 1).

Table 1. Stand densities and volume levels.

Site	Trees ha^{-1}			Basal area (m^2 ha^{-1})			Green tonnes ha^{-1}		
	Initial	**Residual**	**Removal**[1]	**Initial**	**Residual**	**Removal**	**Initial**	**Residual**	**Removal**
1	2891	802	72.3	29	10	65.5	235	85	63.8
2	1699	435	74.4	37	15	59.5	305	130	57.4
3	4202	953	77.3	63	15	76.2	524	130	75.2
4	4156	2533	39.1	29	19	34.5	202	134	33.7
5	2509	0	100	27	0	100	199	0	100

[1]Percent

Figure 1. Tree size distribution for five sites combined.

Felling

The Hydro-Ax 470 feller-buncher was observed for 37 cycles while thinning and 92 cycles performing corridor cuts. The Valmet 603 was evaluated for 125 thinning cycles and 40 cycles working in a clearcut. The Timber King feller-buncher was observed for 34 cycles while operating in a clearcut.

Move distance to the first tree cut after a dump element and distance traveled to the dump pile were estimated from video tape by counting the number of revolutions traveled by the wheel of the feller-buncher as indicated by a white stripe painted on the tires or noting the number of tree lengths traveled. Productivity while thinning averaged 20.6 gt PMH^{-1} (green tonnes per productive machine hour) for the Hydro-Ax and 15.5 gt PMH^{-1} for the Valmet. Cutting out corridors resulted in a productivity of 44.5 gt PMH^{-1} for the Hydro-Ax. The Timber King feller-buncher averaged 67.2 gt PMH^{-1} while clearcutting.

General Linear Models (SAS, 1988) was used to model feller-buncher cycle time for the Hydro-Ax performing corridor cutting and thinning and the Timber King performing clearcutting. Move to first tree and move to dump distances were used as independent variables to model the dependent variables of move to first tree and move to dump time. A dummy variable for the Hydro-Ax was used to distinguish between corridor cutting and thinning. Number of stems was used to model accumulation time. Mean dump time was used in the equation for total cycle time since it was mainly constant and confidence limits at the 95 percent level specified.

Move to first tree distance was found to be significant at predicting move time ($p<0.0001$) and averaged 13.4 m for the Hydro-Ax while corridor cutting and 6.3 m while thinning. The Timber King averaged 11.4 m while clearcutting. The type of function (corridor or thinning) the Hydro-Ax was performing was not significant. Regression equations for predicting move time to first tree are as follows:

Hydro-Ax:

*Move to first tree time (sec) = 0.897377*MoveDist + 2.56651*

MoveDist = travel distance to first cut tree (m)

$R^2 = 0.67$; *C.V. = 39.28; n = 117*

Timber King Clearcutting:

*Move to first tree time (sec) = 0.9470189*MoveDist + 1.596949583*

MoveDist = travel distance to first cut tree (m)

$R^2 = 0.97$; *C.V. = 16.25; n = 34*

The number of stems accumulated in the head were significant ($p<0.0001$) for both the Hydro-Ax and Timber King feller-bunchers for predicting accumulation time. Function was also significant for the Hydro-Ax ($p<0.0001$) and regression equations are shown below.

Hydro-Ax:

*Accumulation time (sec) = 3.99303*Stems + 20.89169*Func + 10.86906*

Stems = No. of stems accumulated during a cycle

Func = 0 for corridor; 1 for thinning

$R^2 = 0.72$; *C.V. = 32.44; n = 129*

Timber King Clearcutting:

*Accumulation time (sec) = 4.978090120*Stems – 1.746217445*

Stems = No. of stems accumulated during a cycle

$R^2 = 0.61$; *C.V. = 39.13; n = 34*

Move to dump distance was found to be significant at predicting move to dump time for both machines ($p<0.0001$) and averaged 12.3 m for the Hydro-Ax while corridor cutting and 5.8 m while thinning. The Timber King averaged 8.5 m moving to dump while clearcutting. Function was also found to be significant for the Hydro-Ax ($p=0.0376$). Equations for predicting move to dump time are as follows:

Hydro-Ax:

*Move to dump time (sec) = 0.6676721*Mtdd – 2.08534*Func + 4.67663*

Mtdd = travel distance from last tree cut to dump pile (m)

Func = 0 for corridor; 1 for thinning

$R^2 = 0.54$; *C.V. = 35.66; n = 119*

Timber King Clearcutting:

*Move to dump time (sec) = 0.7793195*Mtdd + 2.515319618*

Mtdd = travel distance from last tree cut to dump pile (m)

$R^2 = 0.80$; *C.V. = 22.92; n = 34*

Dump time for the Hydro-Ax was statistically the same between thinning and corridor cutting using Duncan's Multiple Range Test (SAS, 1988) and averaged 3.95 sec. Confidence interval limits at the 95 percent level (t=2) were calculated for dump time and ranged from 3.55 to 4.34 sec. Dump time for the Timber King averaged 2.39 sec. Confidence interval limits at the 95 percent level (t=2) ranged from 2.11 to 2.67 sec. Therefore, the true value for dump time for each machine has a 95 percent chance of residing within its confidence interval. Table 2 summarizes time study data for each machine and function.

Table 2. Feller-buncher production for different functions.

Function	Machine	Mean				
		N	Dbh/accum (cm)	Trees/ accum	Time/ cycle (sec)	Green tonnes PMH^{-1}
Thinning	Hydro-Ax	37	7.4	13.8	109.3	22.7
	Valmet	125	7.6	9.6	81.3	15.4
Corridor	Hydro-Ax	92	13.2	6.9	70.4	44.5
Clearcut	Timber King	34	15.2	5.7	51.2	67.2
	Valmet	40	12.2	6.9	63.6	44.3

Skidding

The John Deere 648 grapple skidder was observed for 30 observations across two sites. Standard operation of the skidder included traveling to an area where bundles built by the feller-buncher were ready for transport to the landing, stopping, and then backing up to a bundle for grappling. The operator quickly determined the number of bundles that could be grappled during a particular cycle by scanning what was on the ground. When multiple bundles were combined for skidding the operator traveled in reverse past the number of bundles that were planned for grappling and worked toward the first bundle, combining bundles on the way out.

The skidder averaged 29.6 gt PMH^{-1} and had a mean one-way distance of 680 m. Travel empty distance averaged 346 m and ranged from 162 m to 497 m. Travel loaded distance averaged 334 m and ranged from 165 m to 610 m. Payload averaged 3.1 gt with 69.3 stems $cycle^{-1}$. A summary of measured skidder parameters is shown in Table 3.

Table 3. Summary of skidder production data.

Variable	N	Mean	SD	Min	Max
Travel empty (min)	30	2.03	0.824	0.25	3.45
Position & grapple (min)	30	1.36	0.564	0.28	2.51
Intermediate travel (min)	30	0.90	0.669	0.00	2.56
Travel loaded (min)	30	2.39	1.342	0.58	5.64
Ungrapple (min)	30	0.38	0.179	0.14	0.81
Total time (min)	30	7.07	2.276	1.78	11.05
Total distance (m)	30	680	167.3	326	954
No. of bundles	30	2.3	1.12	1.0	5.0
No. of stems	30	69.3	36.30	21	200
DGL (cm)	30	11.4	2.39	6.6	20.3
DBH (cm)	30	8.1	2.03	4.1	15.2
Distance between bundles (m)	11	66.7	50.12	20	181
Tonnes cycle^{-1}	30	3.13	1.144	1.35	6.07
Tonnes PMH^{-1}	30	29.6	13.36	10.3	55.1

To model skidder cycle time General Linear Models Procedure (SAS, 1988) was used. Travel empty and loaded distances were used as independent variables to model the dependent variables of travel empty and travel loaded time. Distance between bundles was used to model intermediate travel time. Position and grapple and ungrapple times were fairly constant so means were used in the model.

Travel empty distance was found to be significant at predicting travel empty time ($p<0.0001$).

The equation for predicting travel empty time was

$$\textit{Travel empty time (min)} = 0.0076197 * TEDist - 0.6073183873$$

$$TEDist = \textit{travel empty distance (m)}$$

$$R^2 = 0.81;\ C.V. = 18.20;\ n = 30$$

The time required to position and grapple a load was found to be a constant and averaged 1.36 min. Confidence interval limits at the 95 percent level (t=2) were calculated for position and grapple time and ranged from 1.15 to 1.57 min.

Distance between bundles was found to be fairly significant at predicting intermediate travel time (p=0.0071). This model had a lower R-square value than for travel empty time which is probably a result of the low sample size. The equation for predicting intermediate travel time was

*Intermediate travel time (min) = 0.00735*Distbund + 0.5438016119*

Distbund = distance between bundles (m)

$R^2 = 0.57$; *C.V. = 32.49; n = 11*

Travel loaded distance was found to be significant at predicting travel loaded time ($p<0.0001$). The equation for predicting travel loaded time was

*Travel loaded time (min) = 0.0121066*TLDist – 1.651069636*

TLDist = travel loaded distance (m)

$R^2 = 0.76$; *C.V. = 27.80; n = 30*

The time required to ungrapple a load at the landing was also found to be a constant and averaged 0.38 min. Confidence interval limits at the 95 percent level (t=2) were calculated for ungrapple time and ranged from 0.31 to 0.45 min.

DISCUSSION

Harvesting southern pines for energy production will generally mean harvesting smaller diameter trees. In traditional forest management this material might be produced in an early thinning or by treating overstocked even-aged stands. If energy markets develop, intensively managed pine stands may be harvested on shorter rotations with clearcut operations. Conventional equipment (feller-bunchers and skidders) can perform these operations however costs are known to increase as piece size and diameter get smaller.

The system observed in this study used smaller wheeled feller-bunchers appropriately matched to smaller trees. Felling productivity was most affected by the type of cut with clearcutting more than twice as productive as thinning. This is primarily due to the extra time per tree required to select and maneuver in the stand. Assuming a standard machine rate of $100/PMH, the felling cost would be about $5.50/green tonne in thinning and only $1.43/green tonne in clearcutting.

As expected, skidding productivity was simply a function of distance traveled and payload. With the small trees in these stands payload ranged from 21 to 200 stems. This required the operator to collect on average 2.3 bunches to make up a load. Assuming a standard machine rate of $100/PMH, the skidding cost from either thinning or clearcutting would be approximately $3.30/green tonne.

This benchmarking analysis suggests that intensive pine plantation clearcutting will reduce feedstock costs by almost $3.30/green tonne over biomass produced from thinnings. Further cost reductions may result from improvements to feller-buncher cycle time or skidder payload.

ACKNOWLEDGEMENTS

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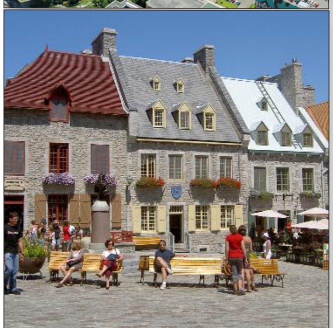

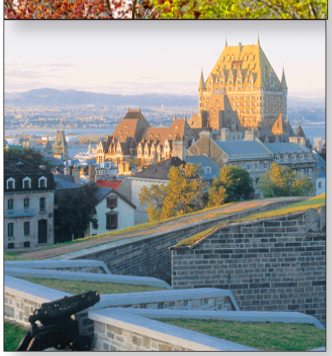

COFE 2011
Quebec city

Spouse Program

Tuesday, June 14, 2011

Guided tour. Reservations should be made before May 31st, 2011. Fee is $80 per person, and includes bus, lunch, and admission for all activities.

The day begins with Touristic Golf in the morning, a 9-hole circuit in the city lets you discover history in a pleasant setting. Putter and ball are provided. Beginners and experienced golfers alike will appreciate the circuit.

After golf, we break for a relaxing two hour lunch at L'Astral (Loews le Concorde), a circular restaurant high above the city. The tables slowly revolve around the centre of the restaurant (90 minutes for a full circuit), offering great views of all the city and St-Laurence River.

In the afternoon, you will be guided through the 125-year old Parliament building, followed by a tour of the Citadel museum.

Fee includes bus service to and from Université Laval. Please take note that this program includes lots of walking around, so wear good shoes.

Welcome to beautiful Quebec City!

Visite guidée. Les réservations sont acceptées jusqu'au 31 mai 2011. Le coût d'inscription est de 80 $ par personne, et inclut le dîner et l'inscription à toutes les activités.

Cette journée commence avec le Golf touristique. C'est un circuit de 9 trous répartis dans la vieille capitale, qui permet d'en découvrir l'histoire tout en s'amusant. Le bâton de golf et la balle sont fournis. Les golfeurs débutants ou expérimentés apprécieront le circuit.

Pour le dîner, nous vous offrons 2 heures de relaxation avec une superbe vue de la ville et du fleuve St-Laurent, dans un restaurant haut perché dont les places assises font un une révolution complète autour du restaurant en 90 minutes : L'Astral (Loews le Concorde).

En après-midi, votre guide vous fera découvrir l'Hotel du Parlement, qui fête ses 125 ans. Et finalement, nous vous invitons à prendre part à la visite guidée du musée de la Citadelle, qui occupera la dernière heure du programme.

Le transport aller-retour des participants est assuré entre l'Université Laval et la vieille ville. Nous vous prions de noter que ce circuit implique la marche pendant la majeure partie de la journée. Des chaussures confortables sont recommandées.

Bienvenue à Québec!

ASSESSMENT OF INNOVATION IN MAINE'S LOGGING INDUSTRY

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ABSTRACT:

Innovation is widely recognized as a critical component to a successful business. The study of innovation in the forest industry is well documented for forest product companies, but there has been very little research conducted on innovation in the logging industry in North America – let alone Maine. In fact, a recent report concerning the future of Maine's forest products industry highlights the importance of innovation to the long-term sustainability of the industry as a whole, but the lack of attention to the logging industry is noticeable. Innovation in the logging industry can be defined as the adoption of a new product, process, marketing strategy, or organization method by a contract logging firm. Currently very little is known about the overall innovation system in Maine's logging industry, nor the criteria contractors use to assess specific innovations.

This paper presents qualitative findings from 10 case studies of logging innovators in Maine. The findings presented here focus on 1) innovations engaged in by logging innovators and 2) the development of mechanized logging systems among the cases studied and how this relates to the available literature. Results show that logging innovators can engage in multiple types of innovation and that logging system development is much more complex that previous studies show with a diverse set of factors and the innovation system influencing development patterns. Results also show a divergent rather than convergent developmental pattern resulting in a wide variety of systems being employed by the cases. In addition this project has outlined a methodological framework for studying innovation that is grounded in a blended innovation model approach collecting both qualitative data through case studies (presented here) and quantitative data through surveys (to be presented in future publications). This study fills a gap in the knowledge and literature on innovation in the forest products industry

INTRODUCTION

Innovation among contract logging firms is an area that is significantly understudied. At this point very little is understood about how logging firms assess innovations, their ability to self develop innovations, and the factors that influence this process. Innovation has long been recognized as a major component of successful and competitive businesses and industries (Schumpeter 1934). Recently innovation in the forest products industry has been a subject of attention in several U.S. states (Innovative Natural Resource Solutions 2005; Hansen 2010), Europe (Kubeczko et al. 2006; Rametsteiner and Weiss 2006), Canada (Anderson 2006), Australia, and New Zealand (Bull and Ferguson 2006). While these studies give some insight into innovation among forest products firms and forest holdings, logging companies have been largely ignored. In 2005 the state of Maine completed the *Maine Future Forest Economy Project*, a comprehensive report on the state and future development of Maine's forest industry (Innovative Natural Resource Solutions 2005). This report states that innovation in Maine's forest industry is a crucial component of its continued vitality and stability. The report also recognizes that logging firms are a major component of the forest industry, but it contains no specifics on these firms or their innovation activities.

The only study available on logging innovation in Maine is by (Vail 1989), which focuses solely on mechanization in the 1980's and does not examine other potential innovation areas. This is also true of logging innovation studies, which have so far focused almost solely on descriptive accounts of mechanization (Rajala 1993; MacDonald and Clow 1999; MacDonald and Clow 2004; MacDonald and Clow 2010). No further study of innovation in Maine's logging industry has been performed leaving a 20 year gap in the study of innovation development in Maine's logging industry. Several other studies have been performed examining logging mechanization in Eastern Canada (MacDonald and Clow 1999) and the Southeastern U.S. (MacDonald and Clow 2010). A study of logging firms in Romania (Duduman and Bouriard 2007) concluded that there was a preoccupation with efficiency and productivity among logging firms and that this grew out of firms struggling to stay in business. Another study from Canada (Anderson 2006) examined innovation among firms providing forestry support services (which included harvesting services) to the Canadian Forest Service and concluded these firms were heavily dependent on suppliers of equipment to develop innovations. This study also found that process innovation tended to be the dominant type of innovation in these firms. Another study from the U.S. Inland Northwest (Allen et al. 2008) found that innovative firms (self scored) had les aversion to financial risk. Results from this study also suggest that larger logging firms could be more innovative than smaller ones. To better understand the development of logging systems employed by logging firms, the innovation activities of these firms, and factor influencing innovation it is important to study these issues from the firm's perspective. Failure to understand innovation among logging firms could negatively impact innovation efforts in the overall forest industry and could lead to a stagnated and less competitive logging industry.

RESEARCH OBJECTIVES

The overall research objective for this project was to understand factors influencing innovation in Maine's logging industry to determine how changes could impact future innovation. The specific objectives were to 1) better understand the development and use of current logging systems by logging contractors, 2) understand the overall innovation activities of logging firms and the driving forces behind them.

INNOVATION DEFINITIONS AND THEORIES

Innovation is an area that has been heavily studied, and dates back to the theories developed by Schumpeter (1934). Since that time the literature on innovation has grown and (Carlsson 2003) notes that there are now over 1,000 published studies on the subject. With numerous definitions proposed (Schumpter 1943, Nelson and Winters 1977, Rogers 2003, OECD and Eurostat 2005, and Rametsteiner and Weiss 2006). Something common to all innovation definitions is a concept of "newness", which includes elements of change and improvement. By far one of the most comprehensive and widely accepted definitions is the one contained in the Oslo Manual (OECD and Eurostat 2005), which is a publication developed to guide cross industry innovation studies in the European Union and Canada. The Oslo Manual also sets the unit of adoption – the level at which something can be considered and innovation – at the firm level. This means that something only has to be new to the firm to be considered and innovation. Another key component of innovation definitions is the recognition of multiple innovation types. The Oslo Manual separates innovation into 4 categories. Table 1 gives a breakdown of these categories, their definition, and examples of each that can be found in logging. For the purposes of this study innovation was defined as: *The adoption of a new product, process, marketing strategy, or organizational method by a contract logging firm*.

Table 1: Definitions of innovation types from the Oslo Manual and examples of each type that can be observed in logging firms

Innovation Type	Definition (based on Oslo Manual)	Logging Examples
Product	Introduction of a new or significantly improved good or service	biomass or road work
Process	Implementation or development of a new or significantly improved production system	new harvest method or equipment configurations
Organizational	The implementation of a new organizational method in the firm's business practices, workplace organization, or external relations	new production tracking system or change in office management
Marketing	Implementing a new marketing method that involves significant changes in product design, placement, promotion, pricing, or other strategies	promotion of special services

One of the most prevalent theories of innovation development and adoption is the diffusion concept outlined by (Rogers 2003), which describes how innovations are developed and how they diffuse through a population. The central component of this concept is the linear adoption process, by which an adopter (individual firm or person) goes about making a decision whether or not to adopt a particular innovation. The process is separated in to 5 phases as highlighted in Figure 1.

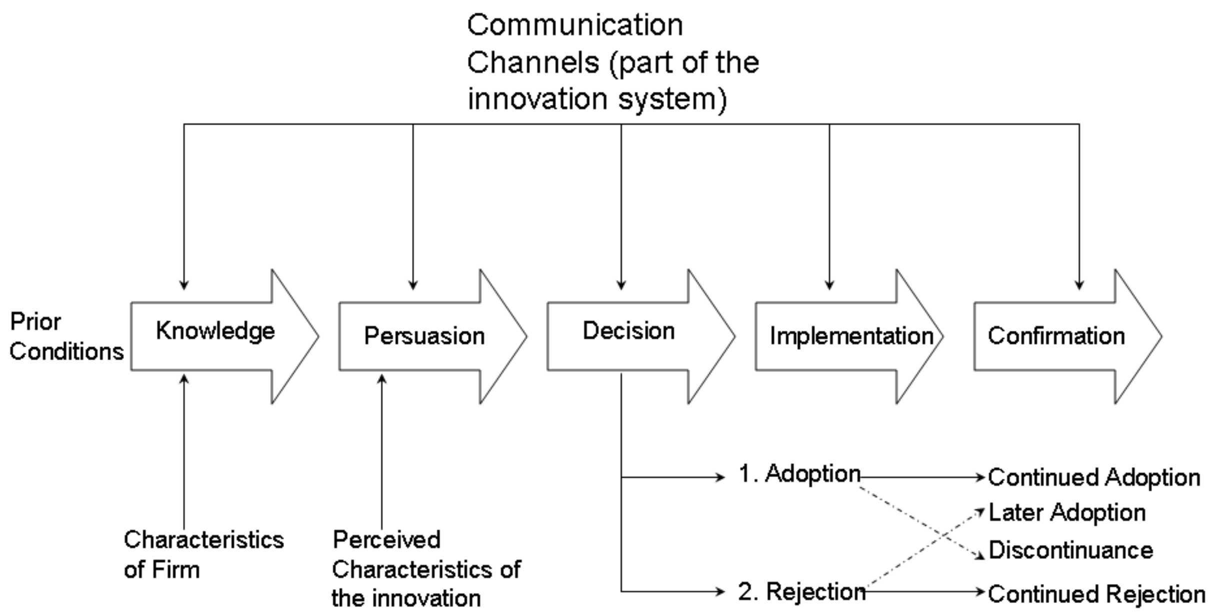

Figure 1: The linear adoption process (Reproduced from Rodgers (2003))

The second major component of the diffusion process is adopter categories, which describe an adopter's innovativeness and the speed at which they develop and embrace innovations. Rogers (2003) separates adopters into 5 different classes: innovators (most innovative and quickest to adopt), early adopters, early majority, late majority, and laggards (least innovative and slowest to adopt).

Another major theory of innovation development is the innovation system. Multiple studies have applied and used this model (Nelson and Winter 1977; Nelson 1993; Rogers 2003; National Innovation Initiative 2004; OECD and Eurostat 2005). The innovation system is a series of interconnected units that influence innovation development and adoption. The Oslo Manual places the firm at the center of this system with numerous connections to other entities. Stone et al. (2011) adapted and refined this model to fit Maine's logging industry based on a series of 10 case studies (see Figure 2).

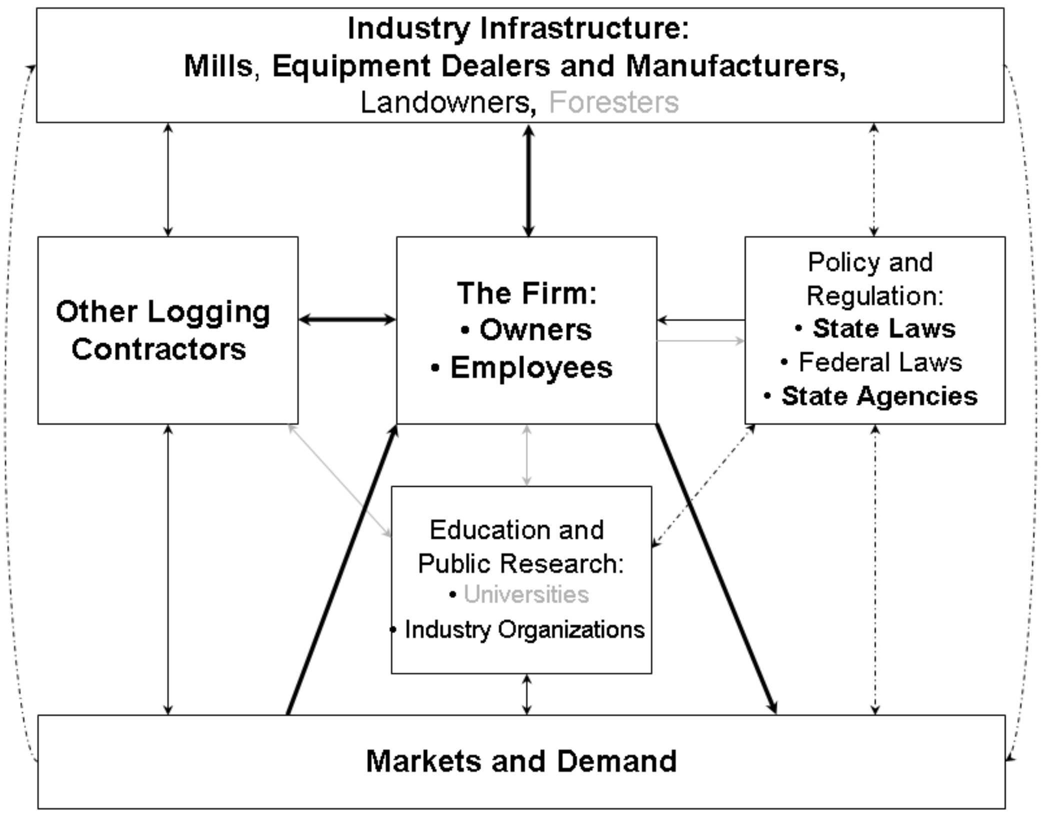

Figure 2: Representation of the innovation system in Maine's logging industry taken from Stone et al. (2011) and based on the Oslo Manual (OECD and Eurostat 2005). Lighter font and arrows represent weaker linkages, while thicker and bolder fonts and arrows represent stronger connections in the system. Dotted arrows denote connections that were not directly tested within this study.

This system and the connections in it can have significant impacts on the innovation types and developmental patterns in a certain industry. It is also possible to blend these two models together, as has been suggested by Rametsteiner and Weiss (2006).

METHODOLOGY

The methodology chosen for this study was a series of case studies of innovative logging firms. Case studies are ideally suited to answering question around why and how phenomenon occur (Yin 2003), so they provided an ideal framework for this study. In addition this study focused on studying logging innovators since they could provide large amounts of information on innovation activities and the development of logging systems. Innovators are also very important to the diffusion process and often serve as opinion leaders in a given community (Rogers 2003).

Sampling innovators represents and extremity sampling technique (Eisenhardt 1989), where cases are pulled from the portion of the population high above the mean.

A mixed mode survey of multiple groups in to forest industry (foresters, equipment dealers, landowners, and others) was conducted to identify innovative logging firms. A total of 154 individuals were surveyed and after removing repeats, wrong numbers, and disconnected numbers an effective sample size of 139 remained. A total of 89 responses were received for the survey leaving an effective response rate of 64%. Participants were asked to: 1) identify logging contractors in the state that they considered most innovative, 2) rank them in order of innovativeness, and 3) explain the firm's innovation activities. Based on the responses potential cases were indentified and a group of 13 firms was selected for the study. They were selected based on how often they were identified, how they were ranked, regional nature of the identifying respondents (identified mostly from one region), and uniqueness of innovation activities. Of the 13 cases selected 10 agreed to participate in the study. Cases represented a variety of firm sizes and included at least one case from each region.

An in-depth semi-structured interview was performed with the owner and key personnel form each firm as well as a visit to one of the company's active sites. On occasion, distance and inclement weather prevented an active site visit, so alternatively previous harvested or inactive sites were included. While this methodology allowed for effective study of system development and innovation activities among innovative firms, its weakness is that it prevents generalization to the entire industry and other adopter classes. To counter this, a survey of logging contractors in Maine was designed and is being distributed at this time. Results from the case studies were used to aid in survey design. At this time survey results are not completed and available, but they can be used in the future to better understand the overall innovation activities of Maine's logging industry and differences between the various adopter groups. Coupling qualitative data from case studies with results from a broad industry or sector wide survey has been shown to an effective method for studying innovation (Rametsteiner and Weiss 2006), and this project is testing this method for application in studying logging innovation in a U.S. state.

RESULTS AND DISCUSSION

Innovation Activities

The logging innovators studied were found to engage in all four innovation categories (product, process, organizational, and marketing). Process innovation was the most frequently engaged in by the cases and also showed the greatest amount of development. Product innovation was found to be the next most frequently engaged in innovation type and showed the second greatest amount of development. Organizational innovation followed process and product innovation in the frequency of engagement, but showed levels of development and advancement on par with product and process innovation. This type showed the most instances of innovation initiated and developed from within the firm using expertise from firm employees. Marketing innovation was engaged in the least by the cases and showed the least amount of development. Several cases did; however, have advanced marketing innovations and were heavily engaged in this area.

Process innovations among the cases typically focused on new equipment or changes to the harvest method and system(s) employed by the firm. Other forms of process innovations encountered included production monitoring devices, on-board machine computer systems with GPS and other capabilities, multiple system integration programs (e.g. combining two harvesting methods and systems), and the use of concentration yards. The focus of process innovation activities among the cases was generally increasing profitability through reducing cost of production and increasing efficiency. The effectiveness of these innovations was measured through a variety of approaches designed to quantify efficiency and cost performance. These systems ranged from general simple systems to highly advanced and detailed tracking systems. That the logging firms studied focus heavily on productivity and efficiency is similar to the findings of Duduman and Bouriard (2007) who suggest that this grows out of these firms struggling to stay in business.

The focus on productivity and efficiency among the innovators studied was moderated by concerns over site quality, harvesting impacts, and aesthetics. The majority of cases focused a great deal of effort on doing high quality work and did not want to sacrifice this for production gains. In these cases site quality became another metric by which process innovations were measured. In fact, four cases stated directly they would close the business before doing sub quality work.

While less prevalent than process innovation, product innovations were frequently cited by cases. Among the cases studied new services (e.g. road maintenance, power line maintenance, specialty harvesting services) were more prevalent than new goods (e.g. biomass, firewood). Product innovations were also heavily integrated with process innovations. Product innovation adoption focused on increasing profits and presented opportunities for business diversification. This also included harvesting services that were simply not provided by other contractors in the area. Success of product innovations was measured through increased profitability, repeat contracts, and client satisfaction.

Organizational and marketing innovations were the least prevalent of the four innovation types, with organizational innovation being much more prevalent among the firms studied than marketing innovation. Organizational innovations were adopted to improve efficiency of operations or improve the information gathering process associated with monitoring operational performance. They were frequently used to measure the success of other innovations along with being used to identify areas for future improvement. This innovation category showed the most internal research and development of the innovation categories, and three cases had even developed complex information gathering systems with specially designed computer programs in house.

The majority of firms studied did not engage in marketing innovations, with only five cases being active in this area. Over half of the cases marketed by word of mouth or contracted primarily with one large landowner and had no need to market the firm. Cases with highly developed marketing innovations were from areas with smaller tract sizes and numerous small landowners. Despite the fact that all contractors in the study were certified by at least one logging certification system (i.e., Certified Logging Professional Program or Northeast Master Logger Program), only two firms used this as a marketing tool. Four cases did state that certification gives them access to timber markets that non-certified contractors do not have.

The results from the case studies show that logging innovators in Maine are capable of engaging in all four innovation categories and self generating innovations. While process innovations were the most prevalent, innovation among the cases was not confined to this area as results by Anderson (2006) would suggest. While the cases studied did state that they were heavily dependent of others in the industry to develop innovations and make them successful; the cases studied did show the ability to self generate innovation, particularly with regard to organizational innovations. Additionally it was found that innovative logging firms often play a major role in driving the innovation system. Logging firms occupy a unique position in the innovation system, as they are the only unit that routinely communicates with others in the supply chain. An innovative logging firm can take a landowner's or mill's need and communicate it to an equipment manufacturer who may then develop a new piece of equipment. Again these findings were unexpected considering the previous findings of Anderson (2006). Contractors also applied equipment in new and innovative ways through new configurations and unique applications. While they may be dependent on equipment dealers to develop the equipment logging innovators are not limited in how they apply it. This often exposes areas for improvement, which logging innovators are often eager to share with equipment manufacturers. In addition there was no difference between larger and smaller firms in the level of development or amount of innovations adopted. This result was unexpected give some of the findings by Allen et al. (2008). Cases identified capital access as the biggest barrier to logging innovation, which suggests that the conclusion by Allen et al. (2008) that firms with lower aversion to financial risk will be more innovative holds true for logging innovators in Maine.

Development of Logging Systems

All of the cases studied had been in business for at least 15 years and although they started with the same system (i.e. chain saw and cable skidder) they now use different logging methods and systems (e.g. cut-to-length, whole tree, or combinations). The cases studied in Maine exhibit divergent rather than convergent paths as Rogers' (2003) diffusion process suggests. This is also in contrast to findings from the Southeastern U.S. which show a trend towards one dominant harvesting method and system (Baker and Greene 2008; MacDonald and Clow 2010).

The mechanization process produced multiple modes of production among the cases studied even though many had mechanized for similar reasons. An illustration of system development in Maine can be seen in Figure 3.

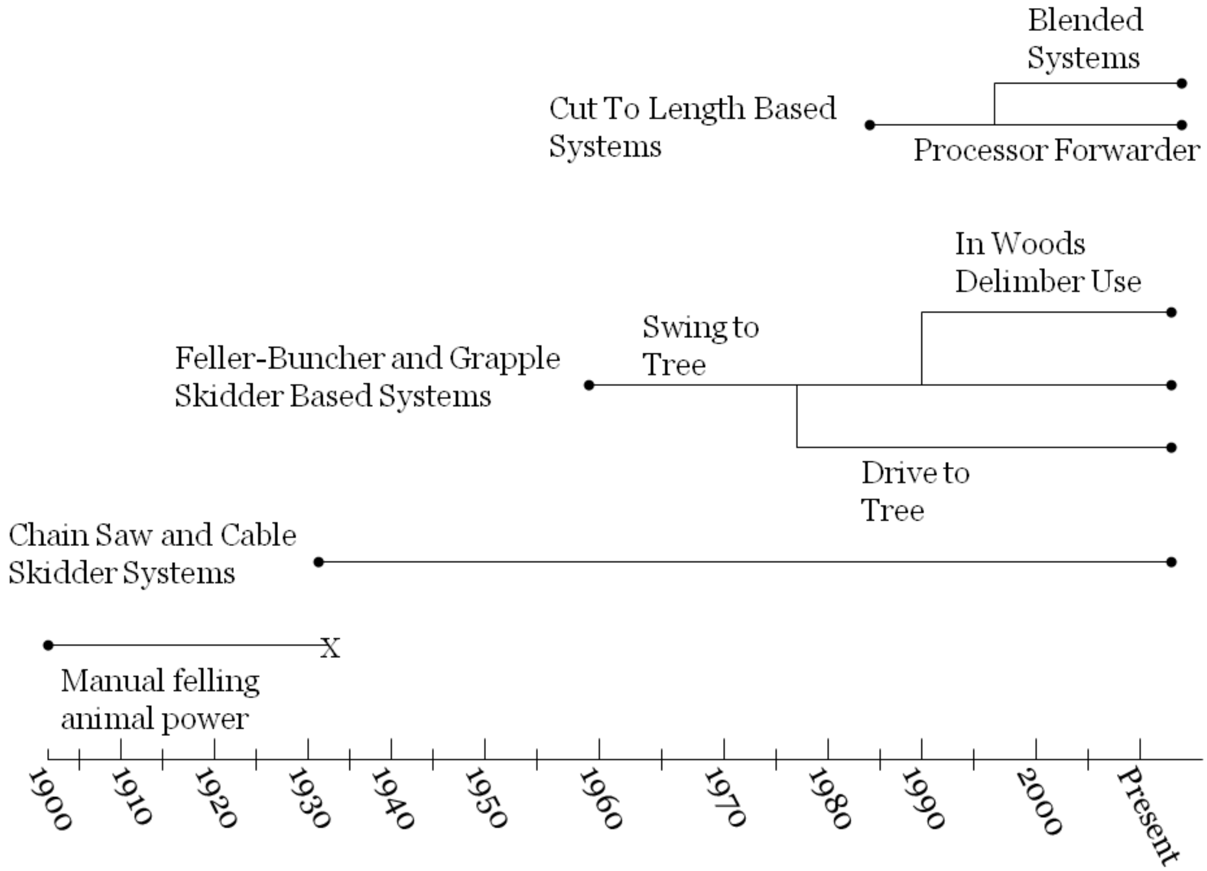

Figure 3: Development of logging systems in Maine over the past century. Compiled from the 10 cases studied and accounts of regional developments by: Vail (1989), Silversides (1988), Richardson et al. (1991), Favreau (1991), and MacDonald and Clow (1999 and 2010).

Contractors cited labor costs and availability, worker compensation insurance rates, the spruce budworm outbreaks of the 1980's, concerns over worker safety, and the need for higher productivity as major reasons for mechanizing operations. These reasons are similar to the conclusions by Vail (1989), but several major changes took place since this article was published. Cut-to-length processor-forwarder based systems were adopted by multiple firms studied in the 1990's. As noted by Vail (1989) these systems have been popular in Scandinavia for some time and were originally developed there. Three cases cited the passage of the Maine Forest Practices Act of 1989 as a major reason for adopting these systems. Contractors utilizing this technology also cited a desire by landowners for thinning services as a reason for adopting this production method.

Still other contractors utilized a tree length system with feller bunchers, grapple skidders, and in-woods stoke delimbers around the same time and for similar reasons. Several cases still utilized this type of system to a degree, but many had abandoned it with some going to cut-to-length systems and other going to whole tree feller buncher based systems with roadside delimbing. The in-woods delimbing system appeared in Maine around the same time as it did in Eastern Canada

(Favreau et al. 1991). A key difference in Maine was that no industry wide studies were performed on this system as was done in Eastern Canada. The contractors utilizing this system had to investigate productivity and effectiveness on their own. Cases were found to have little connection to public research and education components of the innovation system (Figure 2), and no organization such as the Forest Engineering Research Institute of Canada or similar European organizations exist in Maine. In this way Maine resembles the Southeastern U.S. (MacDonald and Clow 2010) more than Eastern Canada (MacDonald and Clow 1999), with no centralized organization to guide or inform innovation efforts in the industry.

The use of multiple systems and production methods by a single firm and the blending of whole tree technologies with cut-to-length technologies by several cases cannot be explained by the division of labor theory or social and policy concerns alone. The non-uniform pattern of development and adoption among the cases appears to be related to how the cases interacted with the innovation system during the development process coupled with the unique challenges that each firm faced in their area of operation. In addition differences in terrain, forest type, regional markets, and forest management goals and techniques of landowners had significant impacts on the systems used by an individual firm, something that is not addressed in the existing literature. There does not appear to be an industry or region wide “winning technology”, rather there is a specific set of innovations tied to the land base and available markets of any given firm. The factors influencing the firm’s linear adoption process (Figure 1) and the structure and important connections from the innovation system (Figure 2) were found to be much more effective at explaining and understanding the divergent development of logging systems among the cases studied.

CONCLUSIONS

The results from the cases studied show that logging innovators can and do engage in all four innovation categories. The innovators studied also possessed the ability to develop innovations from within the firm, though this ability was limited and was largely confined to organizational innovations. Innovative contractors were also found to be a major driver in the innovation system, helping to communicate and identify areas for innovation among many groups in Maine’s forest industry. The innovators studied focused heavily on profitability and efficiency, though this focus was moderated by concerns over performing to a high standard and leaving a high quality site after harvest. Results also show that logging innovators are often dependent on others to develop innovation such as equipment and new forest products markets, but they may apply and use these innovations in new and imaginative ways.

The methodology used in this study has proven to be a robust way of understanding innovation activities among logging contractors through qualitative means. While the cases in this study were limited to innovators the methodological framework can be applied to any adopter class. The case studies also proved valuable in designing the associated survey that will accompany these case studies. While no results from the survey area available at this time, it is expected that the survey results coupled with the case studies will provide a solid understanding of innovation in Maine’s logging industry.

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ICT DEPLOYEMENT STRATEGY IN AQUITAINE WSC: THE EXPLOTIC PROJECT BREAKTHROUGH

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ABSTRACT

French forest-based companies are currently facing an important challenge, the need to increase wood mobilization in order to answer the growing energy and construction markets. The collective target is to harvest an additional volume of 20 millions cubic meters per year by 2020. The challenge is even greater in Aquitaine region. Economic crisis, two destructive storms and recurring insects' attacks will disturb the forest industry for the next ten years. Fighting against these hazards requires innovative business strategies and solutions to improve the day to day efficiency of logging and supply operations.

Better cooperation supported by tools enabling anticipation, agility and real time operations, is the key to achieve this challenge while ensuring added-value creation. ICT deployment is believed to pave this road towards competitiveness as novel technologies will provide operational knowledge-based indicators for forest-based companies.

A coherent and pragmatic extended enterprise development strategy is necessary for successful ICT integration. This extended enterprise concept will allow a demand-driven business model and maximize the value to be generated. A collective R&D strategy was designed by FCBA with its professional partners to meet these challenges. Each project part of this dynamic relies on end-users, their vision and their needs.

A major milestone was reached with the ExploTIC project successful end. This project delivered an open IT architecture. Based on StanforD files, this architecture allows a more accurate harvesting site monitoring and short time control.

Keywords: ICT deployment, StanforD data exchange, Adoption, Wood supply chain, Harvester data.

INTRODUCTION

French National Forest Policy calls for an increase of the wood harvest to face the growing demand from the construction market and the development of the use of wood for energy.

In the Aquitaine region, in South-West of France, this challenge is amplified by the critical consequences of the economic crisis and two large windstorms which hit the region during the last decade (MARTIN 1999 and KLAUS 2009). On a regular basis, 8 Mm3 of Maritime Pine would be harvested in the region as a fair balance to the annual biological growth (Colin et al.

2010) and as to fit wood demand requested by the regional forest-based industry (GIP ECOFOR 2010). But because of the last windthrown and consecutive forest decay due to insects' invasions, it was determined that the annual wood harvest would have to come down to 5Mm3 for at least the five up-coming years (Cavaignac 2010). Stocks available on local wood storage areas and softwood importation from other regions will help reduce this deficit. However, the risks are high that a supply crisis will quickly weaken the Industry and deeply destabilize the existing WSC.

FCBA and its professional partners believe that a way out of this situation would be to:

- Change the way businesses operate into more flexible and adaptive processes;
- Enable better data flow within and between companies to support the upper-mentioned organisation shifts.

Novel process organizations and technologies are key factors of these improvements. Hence, a RTD strategy was elaborated and implemented to propose new methods and solutions to industrial users. This paper will present the chosen methodology and highlight the results already gained from EXPLOTIC, one of the RTD project composing the strategy.

CONTEXT

Wood supply organization in Aquitaine

Forests in "Landes de Gascogne" are mainly covered by Maritime Pine (85% of standing wood volumes, IFN 2010), on flat terrain and sandy soils. Since the 1999 storm, mechanization was considerably developed. 85% of the trees are now harvested by CTL machinery (Emeyriat et al. 2009).

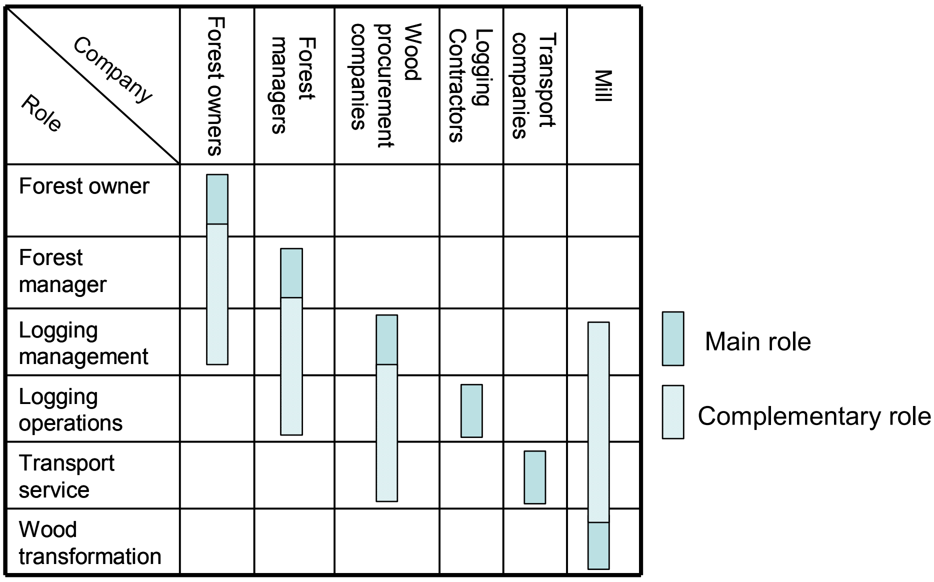


Figure 1 : Roles played by different types of company in the WSC
Rows define the different roles that wood supply chain companies (columns) can assume in Aquitaine.

Like in many other areas in France or other countries, logging operations are mainly done by contractors since wood procurement companies now tend to prefer an outsourcing system.

Many actors are involved in the WSC (see **Figure 1**) from the forest to the mill gate and one company can often play several roles. This results in a complex but flexible organisation of the supply system.

Challenges

Both post-storm crises demonstrated the industry's fragility facing uncommon events. Several weaknesses were pointed out:

- a low knowledge on forest stands characteristics,
- rudimentary processes follow-up methods,
- impossibility to trace logs efficiently,
- Inefficient supply chain logistics management.

Poor data management often appeared to be causing these deficiencies which result in loss or degradation of logs, process waste, and delay in the harvest, the transport or more generally speaking the whole WSC management.
Before Klaus (2009), the Industry remained competitive despite these problems thanks to the advantage created by an easy access to abundant raw materials. But now that the resource has been deeply reduced, it has become urgent to developed new strategies to harvest and use wood more efficiently.

This evolution requires first an increase of day to day efficiency in the logging operation management that will finally lead to a global yield optimization from standing trees purchase to mills process. In such perspective, access to information is critical and data management must be enhanced using ICT.

In practise, a long term step by step strategy based on targeted ICT integration is required to implement this new wood supply chain management method. This strategy needs to combine (Ginet et al. 2011):

- Automation of standardized data transfer,
- A better technical and financial monitoring of harvesting blocks, stock piles, machines, transportation services and operators.
- Short time control,
- Optimization of wood resource allocation by transforming wood quality characteristics expected by the process in trees description parameters (Moreau 2010),
- Decision support and predictive tools to locate stands, harvest trees and deliver logs with a better match with the industries specifications (Vuillermoz & Arraiolos 2010).

METHOD TO SUPPORT ICT DEPLOYMENT IN AQUITAINE

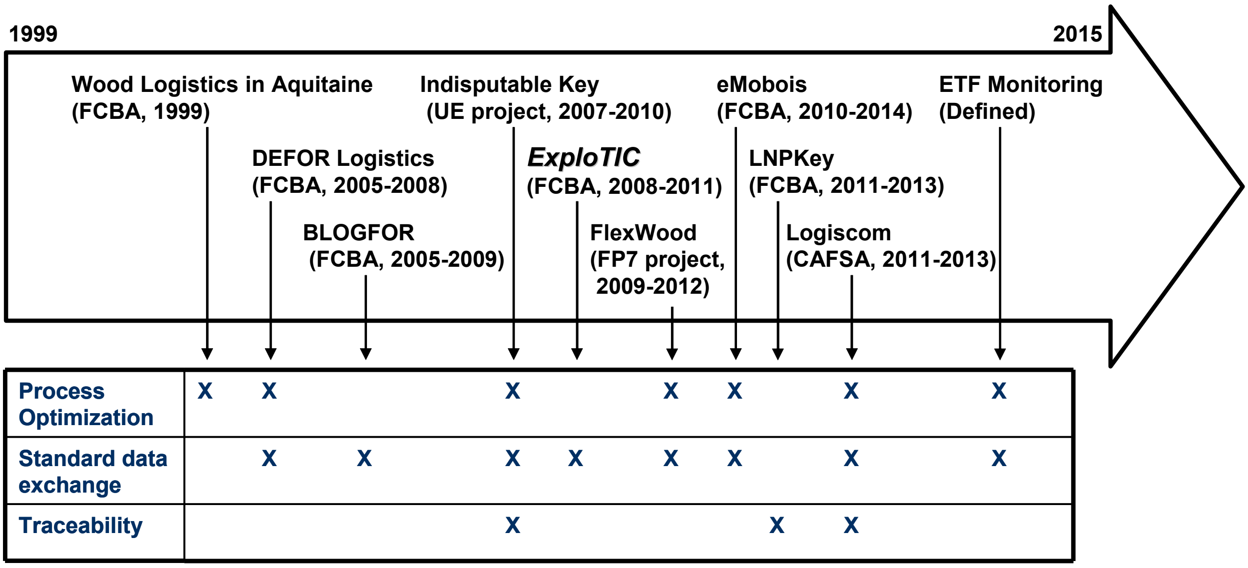
Creation and implementation of the RTD strategy

A collective R&D strategy was designed by FCBA with its professional partners to find solutions to the up-mentioned challenges. Each project part of this dynamic relies on end-users, their vision and their needs.

Starting from a need analysis, each project goes through a technology benchmarking, a development phase followed by integration on test sites. Following this method, it becomes possible to develop prototype and test them in real conditions. Test runs results provide input for process redesign of the prototype as well as clear specifications of ICT tools needed to achieve the targeted redesign. With a valid proof of concept, transfer can be organised so that the novel system or solution can be offered to the industry.

In Aquitaine, this integration started in 1999 and is still running. ExploTIC as a project is part of this global approach (**Figure 2**) and

Figure 9 in APPENDIX also shows where the project stands in the overall IT deployment.



Aquitaine ICT R&D projects timeline and issues. A long term step by step strategy based on targeted ICT R&D projects is required to implement a innovative wood mobilization system. R&D projects deal with three types of issues : process optimization, standard data exchange and traceability. Each project has at least one direct application in Aquitaine.

Figure 2 : Aquitaine ICT R&D projects timeline and issues

ExploTIC project genesis

EXPLOTIC started from the diagnostic that IT functionalities within the harvesting machines were completely under-used by both the contractor and the supply companies though these tools are often key facilitators towards:

- Reliable data exchange between the field and the office
- Better machine utilisation rate

EXPLOTIC mission was to provide tools and solutions for operational production data transfer between harvesters, forwarders, contractors and wood supplying companies in order to better handle organizational issues, e.g.:

- Increasing data exchange quality and reliability between field and office with any machine working in the “Landes de Gascogne”.
- Decreasing wood supply companies’ employees road travel of 50%,
- Improving machines utilization rate.

A collective project from the start, ExploTIC associated representatives from the Aquitaine Industry (Smurfit Kappa Comptoir du Pin, Forestière de Gascogne, CAFSA, Castagnet-Duméou), machines manufacturers (Ponsse and John Deere) public authorities (Agriculture Ministry and Aquitaine regional council) and FCBA (acting as coordinator).

Method applied during the EXPLOTIC project

From the very beginning, the project scope was clearly bounded:

- The solution shall be build on a maximum number of existing technologies
- It should be interoperable with every machines working in the region.

The project began with an end-users needs analysis. Ten contractors, four supply companies and two forest machines manufacturers were interviewed. Directly involving contractors in an IT project was a first for those professionals who are often seen as too small business to participate in such dynamics. In addition to this analysis, a technology benchmarking was run on existing harvester-embedded software and foreign practices. A trip in Finland was organised with a group of users to see on in the field how StanforD standard is implemented.
The next step consisted in designing the IT Architecture that would enable standforD-compatible harvester-data exchange while overcoming the lack of inter-operability from the IT component installed in the machines at the time. Exchange sequences were built for logging sites organisation, implementation and monitoring. A working group including end-users was involved in this architecture and software specification work. The latter was mostly dedicated to choosing StanforD variables and transforming it in a relational database. This task was based on UML sequence, use case and class diagrams.

Once specified, development started in an iterative way under close watch from the end-users group. Easy-to-use guidelines were produced to explain how to run the IT system on a regular basis.

The ExploTIC IT architecture was then tested and validated on a test site of more than 20 machines, 5 contractors, and 4 supply companies (**Figure 3**). Implementation involved wood procurement companies and logging machines owners distributed in four sub-groups – each with its own characteristics – in order to cover most "Landes de Gascognes" cases (**Figure 3**).

	Supply Companies	**Machines owners**	**Implementation characteristics**	**Machines characteristics**
1	CAFSA	AFM Pereira SARL Palomo	The contractor works for several sub-contractors and to wants to use StanforD data to its own	Network connected Ponsse machines Non-computerized machines
2	Forestière de Gascogne	SARL Valeiro SARL Eurobois SARL Labat	A lot of contractors working mainly with forestière de Gascogne	Network connected Ponsse and John Deere machines Non-computerized machines
3	SKCDP	SKCDP SARL Deyres	A mix of wood procurement company' machines and contractor machines. A compatibility with Smurfit group data security strategy is required	Network connected John Deere machines (D an E series) Non computerized excavators with felling head.
4	Société Castagnet-Duméou	Société Castagnet-Duméou	The wood procurement company only works with its own machines.	Not connected John deere machines Non-computerized machines

Figure 3 : Test sites organization

Tests sites requested regular intervention and monitoring in order to:

1. Analyse the existing sequences and the means used to exchange data,

2. Update the existing system by connecting available IT, integrating the missing ones and redesigning data model
3. Train the operators on the easy-to-use guidelines,
4. Control all the data exchanged over the IT Architecture and also received by FCBA office,
5. Assist operators to improve their skills in the system use,
6. Gather enhancements requests.
7. Specify and follow-up debug developments requested to the software services company.

Field tests were also a good opportunity to run a cost/benefits analysis and identify the benefits the system would bring to the logging process. Potential gains can trigger user interest. It was therefore a prerequisite to the design of the broader deployment strategy that was finally presented and validated by both professional and instutional representatives.

RESULTS

Lesson learnt from the Need Analysis

First analysis revealed the incompatibility between harvesters' software from different manufacturers. At that time (2008), Timbermatic 300, Timberoffice 4.0 and Opti 4G 4.6 were the last versions of the software available. They were able to write StanforD data, but they did not meet the standard format. Hence writing and sending a file from one brand's software made it impossible to read in another. Some variables were mandatory for the exchange but were defined as optional in the software interface. This standardization failure was obviously calling for the specification and development of an interoperable solution.

The needs analysis also showed that a special attention should be paid to the project acceptability by contractors. Their main reluctance came from the fear that time monitoring done by the harvester computer would be transferred to sub-contractors. Such data exchange would reduce contractors' autonomy and negotiation capacity on contracting rates.

An other initial barrier was the logging contractors' lack of awareness of what could be gained from by better management of production-data.

The needs analysis was concluded by a redesign of logging operations monitoring and control procedures based on the use of StanforD data exchange.

ExploTIC IT architecture

StanforD data included in apt, prd, prl and drf files were fully parsed and analysed to understand which variables would fit the businesses needs. The needed information were sorted into groups (**Figure 4**) and structured in a relational database model. Each table attribute from this model is linked to StanforD variables (**Figure 5**).

Data group	Role	Details
Structuring data	Allow data aggregation by creating an unique referential for each company	Wood products Species Product groups Machines Persons and companies
Site management data	Data required to plan and prepare a site	Harvesting sites data Bucking Instruction Production order
Field data	Data sent back from machines	Harvester production Forwarder production Time monitoring data

Figure 4 : ExploTIC data groups

Analyzed data were sorted in order to clearly identify which ones met the industry needs.

Time monitoring data	
Attribute name	**StanforD variable**
ID	Explotic internal variable
activityDate	Var53_t1
activityDuration	Var316_t1:t23 or var317_t5 or var319_t5 Depends on activityTypeID
CreationDate	Explotic internal variable
activityTypeID	Var316_t3 or var317_t3 or var319_t3 Depends on activityTypeID
OperatorID	Var212_t1
MachineID	Var3_t1
SiteID	Var21_t1

Figure 5 : An exemple of data modelization and StanforD linkage

Each ExploTIC database model table attributes is defined and linked, when it is required, to StanforD variables. These information ensure the compatibility with the standard.

This data analysis was approved by the end-users group and was then used as a basis for the definition and development of the system architecture. The decision was taken to specify and develop a StanforD compatible software.

Data transfers between existing machines' IT systems and ExploTIC software were designed (Figure 6) and development was assigned to SDIGIT (a forestry software services company).

The delivered ExploTIC software enables:

- Field data creation and exportation in a StanforD format for non-computerized machines' operators,
- StanforD bucking instruction (APT files), harvester (PRD files) and forwarder (PRL files) production and monitoring data (DRF files) importation and aggregation inside a unique database for machines and logging managers.
- Connection to other databases through an opened SQL engine.

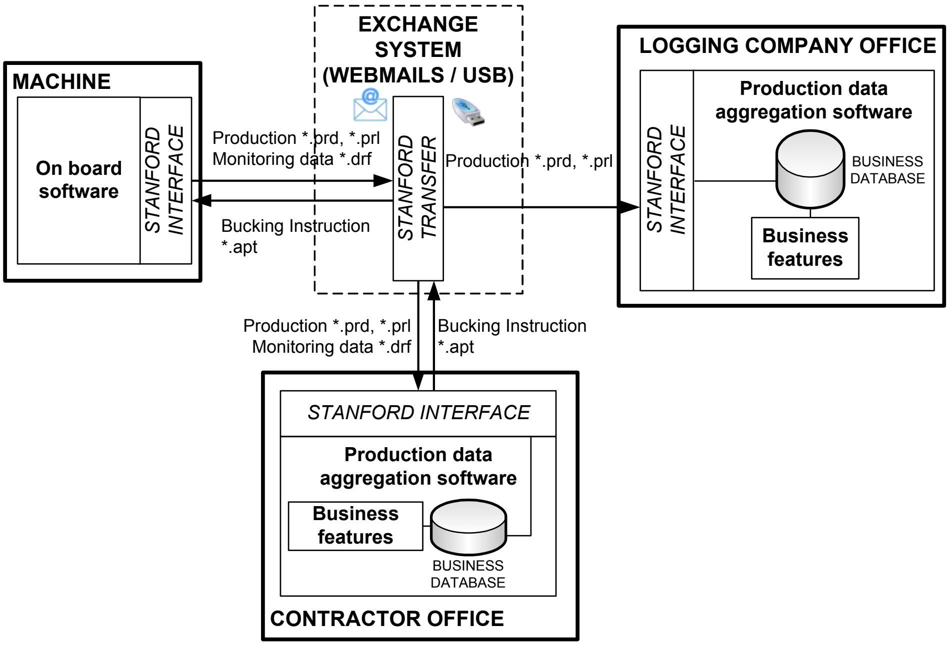


Figure 6 : ExploTIC ICT architecture
The architecture model shows the different data exchange possibility and the means used between the involved actors.

The major innovation is the connector role of this application. The database is opened (firebird base) and the SQL engine easily allows new additional modules for data treatment and connection to any information system.

Training tasks were anticipated by writing easy-to-use guidelines, based on screenshots and illustrated procedures.

A pilot to demonstrate EXPLOTIC efficiency

These experiments showed that the system could cover most of the possible cases: from companies equipped with different machines (Ponsse, John Deere…) to non-computerized ones (**Figure** 7).

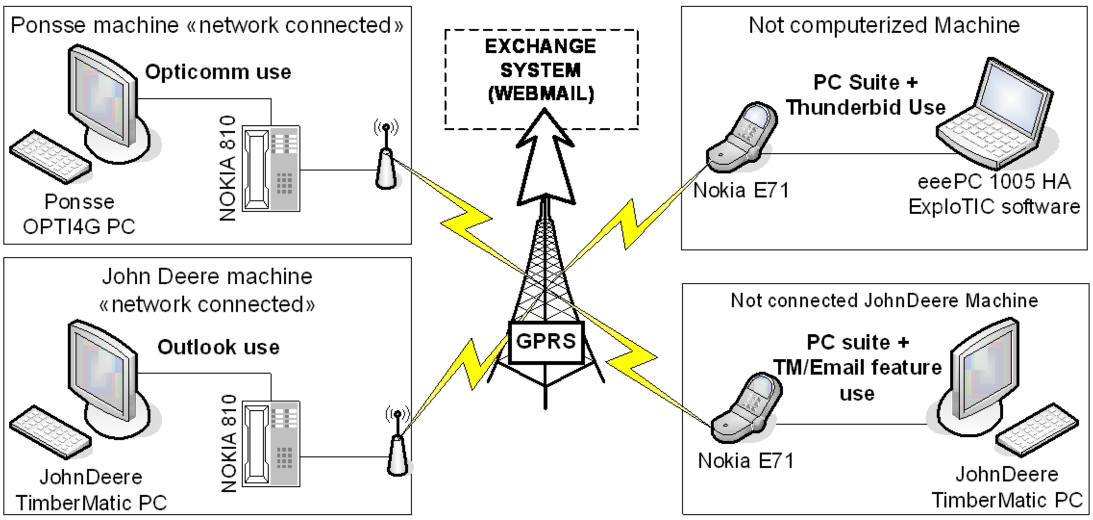


Figure 7 : ExploTIC system adaptation to any cases
The four cases treated covers the different machines configurations met on the "Landes de Gascogne" Forest. These tests were extended and successful in 2011 on new machines series (Opti 4G 4.7 and Timbermatic H09).

During these tests, bugs and features requests concerning ExploTIC software but also John Deere and Ponsse solutions were identified and relayed to the development teams involved. Finally, the conclusion of this pilot is an operational system and directly measured benefits.

Measured benefits and costs

Once connected to data treatment system the ExploTIC architecture can provide the following improvements:

- Accurate harvesting sites profitability analysis,
- Day to day production quality control with time expenditure reduction,
- Detailed operators time sheet justification,
- Contractors services rates negotiation tools,
- Logging operations customization depending on sites characteristics,
- Machines preventive maintenance alerts,
- Price matrix optimization,
- Roadside stock piles volumes anticipation.

ExploTIC leads to a better match between harvest and mills needs and gives an increased operational efficiency in logging operations management, both for contractors and wood-supplying companies.
Regarding the adoption challenge, operators were less reluctant to use data transfer after a few weeks of use. Such is showed by the following testimony by Loïc, an operator from Castagnet-Duméou Company:

> *«First, I was thinking that ExploTIC was only used by my boss to control my work. After two weeks, I realized that it reduces the time spent each week to count my work time and production volume and to write it on my diary – especially as the company clerks must type this data again at the office. But, it was even more useful the day I had to prove that my productivity was decreased because the former week, I had been ordered to change three times of site and I had spent more time in roads travel. Finally, this system is as useful to me as it is to my boss.»*

The deployment cost was also estimated. The identified expenditure items are operator time consumption, machine immobilization, consultant services, training sessions and software investments. An average calculation shows that it will cost 9 600 € to a contractor owners of three machines (**Figure 8**).

Machines expenditure items		
Operator time consumption and Machine immobilization	1.5 days in training 0.5 day of machine immobilization for IT deployment	2 000 €
Consultant services	1.5 days per machine	1 200 €
Training session	1.5 days	1 200 €
Software investments	ExploTIC : for free	0 €
TOTAL		4 400 €
Office expenditure items		
Executive time consumption	1 day in training 1 day for data redesigning	2 000 €
Consultant services	3 days per company	2 400 €
Training session	1 days	800 €
Software investments	ExploTIC : for free Integration to the existing information system	0 € 0 € for excel connection until 40 000 € for a complete integration into an ERP
TOTAL		From 5 200 € to 45 200 €

Figure 8: Detailled expenditure items
Deployment cost is calculated by estimating the time spent and IT investment cost. This data were gathered during on-field tests.

In France, professional training is well subsidized and such collective project can be partly founded by public authorities. This cost will be reduced to an estimated cost of 2 500 € for each logging contractor. Thus, this cheap deployment investment encourages the ExploTIC system adoption by small businesses.

EXPLOTIC AND AQUITAINE ICT DEPLOYMENT OUTLOOK

Next steps towards a real-scale ExploTIC deployment in the overall Aquitaine region

The next step consists in deploying this IT system on 200 forest machines, 80 contractors and 4 main wood supplying companies. This deployment will be completed in 3 phases:

- Industrialization of the ExploTIC software to make it more robust and consolidate its functional scope,
- Training engineering in collaboration with a professional training centre and involving directly forest machines operators and logging operations supervisors,
- Train users and deploy the system within 2 years.

Training of users, software installation, support to company data redesign and software updates will be included in a global ExploTIC services package. Each deployment on a given machine or in a given office will require the global package to be successful.

ExploTIC project position in the overall Aquitaine IT deployment

The ExploTIC is a breakthrough in the whole round wood mobilization system. Future RTD projects will be able to build on this IT architecture when even they require digitalized data transfer between offices and machines.

New developments must now concentrate on improvements for contractors business. As pointed out, there is an urgent need to develop tools using StanforD files and dedicated to operations monitoring and control. The concept currently defined consists in crossing production, financial and resource management data at the machine, the site and the global business scales. This data treatment shall be integrated in dashboard software which will give to logging contractors the proper tools to monitor, to control and to anticipate logging operations. This future project is the key to increase efficiency at the operative level and to think innovative business strategies.

At the same time, results of other European and French projects concerning the same topic must be integrated in the Aquitaine deployment plan.

For example, the French eMobois project concerns a global standard data exchange system which will provide web services for exchange automation and advanced business features (geolocalization, wood products national referential, online administration). A demonstration site is planned in Aquitaine (Ginet et al. 2011) and will be implemented in the current ExploTIC Architecture.

The European Flexwood project aims for a more flexible supply chain using novel IT developments in logging activities, namely:

- Forest plot characterization by aerial and terrestrial LIDAR analysis,
- Bucking instructions optimization,
- Sawn wood specification transformation in standing timber characteristics.

In Aquitaine, a study case is underway. Aerial and terrestrial LIDAR acquisitions benefits in wood mobilization businesses are currently tested. The experiment consists in testing how LIDAR data can contribute to optimize supply operations in accordance to the clients' demands (Vuillermoz & Arraiolos 2010). Here, ExploTIC bucking instruction and harvesters production implementation allows optimized bucking control.

CONCLUSION

A long term approach is required for an efficient ICT deployment and use by the round wood mobilization Industry. In this business, resistance to change is strong. Any innovation proposal must be concrete and well justified to be accepted and implemented. However, this strategy is binding. The main difficulty is to keep in mind that final goal of any novel ICT integration project is to increase business efficiency and leads to a demand-driven model. Communication and training are often overlooked by professionals whereas they are keys to this strategy success.

Finally, this global approach must keep being driven by continuous improvement. Each business shall take ownership of projects results and adapt it to its own case. Therefore, offering flexible solutions is required. Thus, in Aquitaine, once a RTD projects gives positive results, FCBA and private consultants work together to transfer and adapt novel technologies into wood supply chain companies.

The ExploTIC IT architecture deployment respects these requirements – Flexible solutions, communication and training. Tests sites demonstrated the deployment feasibility in any types of businesses. Communication was central to the project, as every logging activity stakeholders has been implied during each phase. The ExploTIC delivery package was defined to guarantee a successful widespread deployment.

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APPENDIX

Wood mobilization activity	IT improvement	Forest owner	forest manager	Logging management	Logging operations	transport	wood process	R&D and transfer projects	Projects status
		Roles concerned and deployment status							
Standing wood purchase	➢ Plot characterization	R&D	R&D	R&D				FORSEE, Flexwood	Underway
	➢ Timber quality modelisation			R&D				J Moreau thesis	Completed
Mills roundwood order	➢ Sawn timber specifications transformation to roundwood specifications						R&D	J Moreau thesis	Completed
Logging sites planning	➢ Harvest potential estimation by confronting mills specifications to plots characteristics			R&D				FlexWood	Underway
	➢ Bucking instruction creation			√				**ExploTIC**	Underway
	➢ Bucking instruction optimization			R&D				FlexWood	Underway
Works organization	➢ Bucking instruction dispatch to contractors			√				**ExploTIC**	Underway
Sites monitoring	➢ Harvesters production dispatch to logging agents and machines managers			√	√			**ExploTIC**	Underway
	➢ Time monitoring data dispatch to machines managers				√			**ExploTIC**	Underway
	➢ Machines efficiency monitoring software				X			ETF Monitoring	Defined
	➢ Sites efficiency monitoring software			√	X			ERP project ETF monitoring	Completed Defined
Roadside stock piles follow-up	➢ Forwarders production dispatch to logging company			√				**ExploTIC**	Underway
	➢ Wood stock piles traceability			X				Logiscom	Defined
	➢ On field wood inventories data entry			X				Logiscom	Defined
Transportation planning	➢ Available stock calculation			X				DEFOR	Completed
	➢ Transport orders planning descision support and creation software			X				DEFOR	Completed
	➢ Transport orders dispatch to transport company/managers			X		X		eMobois	Underway
Transport organization	➢ Transport tours planning optimization tools			X				Logiscom	Defined
	➢ Truck tracking services			√					
	➢ Load acknowledgment			X				Logiscom	Defined
Mills roundwood receipt	➢ Delivery receipt dispatch to logging / transport companies and managers			X			X	eMobois	Underway
	➢ Roundwood orders monitoring tool						X	DEFOR	Completed

X : Improvement to acheive ; √ : Improvement acheived ;
R&D : Research and development underway

Figure 9 : ICT contributions to the Aquitaine roundwood mobilization system through R&D projects

INFLUENCE OF WOOD VALUE ON OPTIMAL TYPE OF THINNING

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ABSTRACT

It is commonly understood that thinning reduces competition for growing space in forest stands. Reduction in competition enables residual trees to maintain or even increase growth. Since it is commonly accepted that bigger trees are more valuable, thinning is often assumed to improve overall stand profitability. On the other hand, formal financial analyses of thinning often show treatments to be an unprofitable venture even if residual trees show improved growth rates. Analysis of literature suggests that wood value is commonly an overlooked aspect in the general understanding of thinning profitability. The relationship between wood value and type of thinning (i.e. choice of trees to remove) was studied to determine whether certain types are intrinsically more profitable than others, and, to determine if wood value could be used to identify optimal type of thinning.

Results indicate that wood value has an important influence on the type of thinning that is financially optimal. No single type can be said to always be the most or the least profitable. Presenting wood value as a function of stem size makes it possible to see underlying mechanisms of thinning profitability and greatly enhances one's understanding of which tree sizes to remove in thinning and which to leave to increase profitability. Considering the relationship between wood value and stem size can increase one's understanding of stand profit production and lead to consideration of stand interventions with higher profitability than those suggested by commonly used guidelines, which are rather designed for maintaining biologically desirable stock levels.

Keywords: Type of thinning; profitability; wood value; profit-size relationship

INTRODUCTION

Landowners, like other stakeholders in the wood supply chain, aim for reasonable profits on their capital. With the shift from simply harvesting natural stands to actively managing wood production, landowners have been investing more in their stands through the implementation of a variety of silvicultural treatments. Nowadays, silviculture regimes can be designed to influence tree and stand characteristics towards a desired state. Unfortunately, even if trees grow exactly as planned following a treatment, the endeavor may well be unprofitable for the landowner.

Part of the explanation for this apparent discrepancy is that net value of wood depends on many factors unrelated to tree and stand characteristics, such as the distance to processing facilities. The net value of a tree can vary widely simply by the facts of different harvesting systems or product recovery schemes. In other words, two identical stands subjected to the same silvicultural treatment and yielding the same amount and quality of wood can have very different profitability outcomes.

Thinning is a good example of a silvicultural treatment for which we have difficulties understanding the influence on profitability. It is commonly understood that thinning reduces competition for growing space in forest stands (Smith *et al.* 1997). Reduction in competition enables residual trees to maintain or even increase growth. Since it is commonly accepted that bigger trees are more valuable, thinning is often assumed to improve overall stand profitability. On the other hand, formal financial analyses of thinning often show treatments to be an unprofitable venture even if residual trees show improved growth rates (e.g. Stone 1993).

The type of thinning, also referred to as "method" or "application" of thinning, indicates the choice of trees to be removed and of those upon which future growth will be concentrated. The type of thinning has a direct influence on many of the cited benefits of thinning such as the opportunity to change stand composition and the salvage of anticipated volume loss. Furthermore, it is said that type of thinning allows the improvement of a stand's financial outcome by "favouring the trees of best potential quality and discriminating against the poor ones" (Smith *et al.* 1997).

Forestry textbooks usually present four distinct methods in terms of their known ecologic and biologic influences: i) low, ii) crown, iii) selection, and iv) mechanical thinning (Daniel *et al.* 1979; Nyland 1996; Smith *et al.* 1997). Textbooks take care to mention that the chosen type must usually be a balance between biological and financial implications. Unfortunately, if one wants to determine the most profitable type of thinning for a specific situation, little information is actually available on the interaction between wood value and type of thinning.

Price (1985; 1987; 1989) examined the economic theory of thinning with some emphasis on the distribution of increment among different tree sizes, given prevailing wood value. His work, like others on the economics of thinning (e.g., Stone 1993; Stone 1996; Valdez-Lazalde and Lewis 2000; Hyytiainen and Tahvonen 2002), focused on determining how different thinning variables (intensity, type, timing, number of treatments within a rotation, etc.) influence thinning profitability, given prevailing mean wood value at some point in time. Sensitivity analyses to changes in wood value were performed but the studies did not intend to specifically explain the influence of wood value on the relative profitability of different types of thinning. Price (1989) concluded, like many others, that *"…no general case for or against thinning can be made, nor for any particular form of the operation. A particular thinning regime is only justified by a favorable balance of results achieved in particular circumstances*".

In this work, we decided to flip the focus around. Instead of investigating the influence of thinning on profitability given wood value, we investigated the influence of wood value on the profitability of different types of thinning. The goal was to determine if and how financially optimal type of thinning is dependent on wood value. This work is part of a bigger research project on the influence of wood value on profitability of thinning, with the intent of improving our ability to design profitable thinning regimes.

PROFIT-SIZE RELATIONSHIPS - AN ADAPTED WOOD VALUE FORMAT

We recognize that each stand has its own context within the wood supply chain, resulting in specific streams of costs and revenues throughout a rotation. In order to determine the influence of wood value on the profitability of different types of thinning, we used a wood value expression that allows every unique situation to be considered on the same basis. Thinning being a treatment whose main influence is on stem size produced and type of thinning being the determinant of tree sizes to be harvested, we chose to use wood values presented in the form of profit-size relationships.

A profit-size relationship is a summary of all costs and revenues that a landowner would encounter given his specific value recovery chain. The resulting net value of wood is related to stem size following the procedure described by Soucy and Kershaw (2011). Profit-size relationships provide a clear picture of actual financial contribution of different tree sizes, given a landowners particular context. This format of wood value makes it possible to interpret how wood value interacts with thinning profitability (Soucy and Kershaw 2011).

For this investigation, nine general shapes of profit-size relationships where developed (Fig. 1) and guided the creation of 166 specific profit-size relationships representing a wide range of forms and magnitudes. The range of wood values used covered not only likely values but also a variety of extremes, in order to facilitate the identification of interactions.

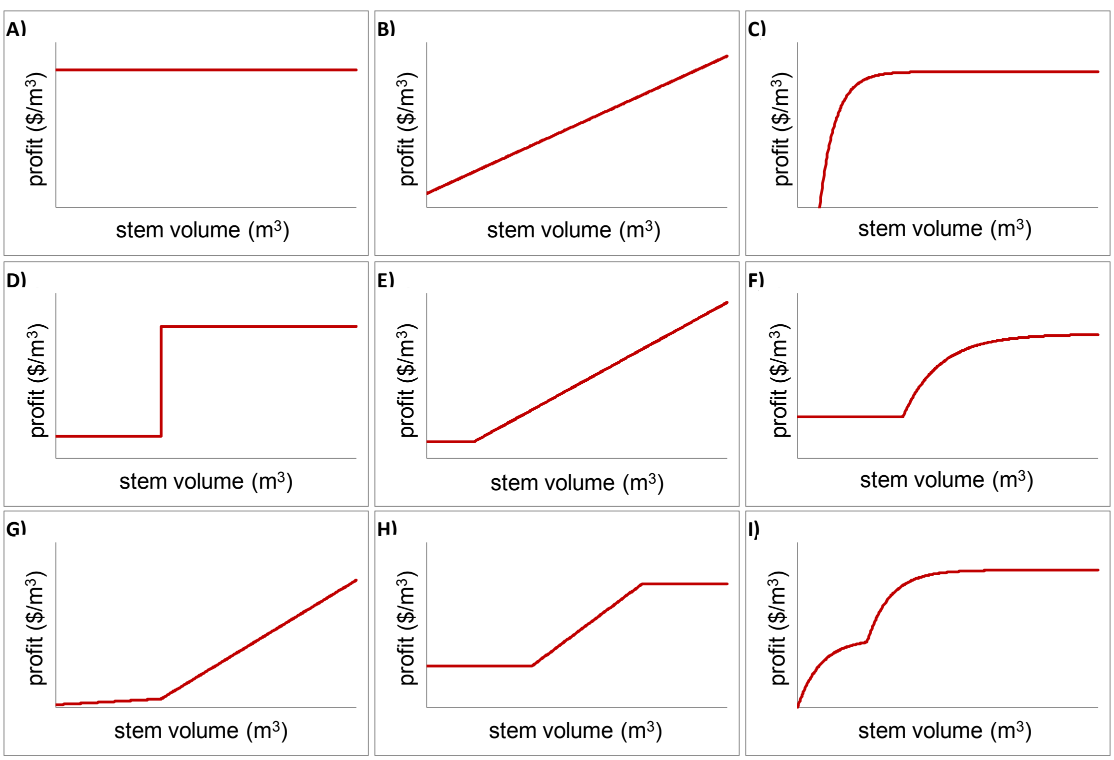

Figure 1: General shapes of profit-size relationships considered. A - constant wood value; B - linear relationship with a positive slope; C - logarithmic relationship; D - constant relationship

with a step change in value; E - constant value with a change to a linear relationship with a positive slope; F - constant relationship that changes to a logarithmic relationship; G - linear relationship with a positive slope that has a change in slope at a set stem volume; H - constant relationship with a change to a linear relationship for a range of stem size after which in remains constant; I - logarithmic relationship with a step change to another logarithmic relationship.

Approach used

To investigate the influence of wood value on the profitability of different types of thinning, we designed 12 types of thinning to cover the spectrum of stem size combinations that can be harvested (Figs. 2 and 3). We compared, through simulations, the expected profitability of the 12 types of thinning applied to a single stand, for each of the 166 different profit-size relationships. To facilitate the interpretation of results, we assumed that the stand's response to the 12 types of thinning was a complete redistribution of the growth potential of the trees removed (i.e stand volume growth was kept exactly the same as if the stand had not been thinned). For each wood value scenario, thinning profitability was measured and the performance of each type of thinning was ranked. The results of each scenario were compared to identify reasons or contributors that explain why a particular type of thinning was more or less profitable than the others.

Initial stand conditions were based on plot data from a loblolly pine thinning experiment provided by the Loblolly Pine Growth and Yield Research Cooperative (Ralph Amateis, Virginia Polytechnic Institute, Blacksburg, VA, pers. comm. 2008). In each case, we assumed a removal of 35% of stand volume by the thinning. The profitability criteria used was Net Present Value (NPV) of a single rotation (Davis *et al.* 2001), assuming a 3% discount rate. More details on the analysis and an example of the data and figures used to perform the analysis are available in Soucy (2010).

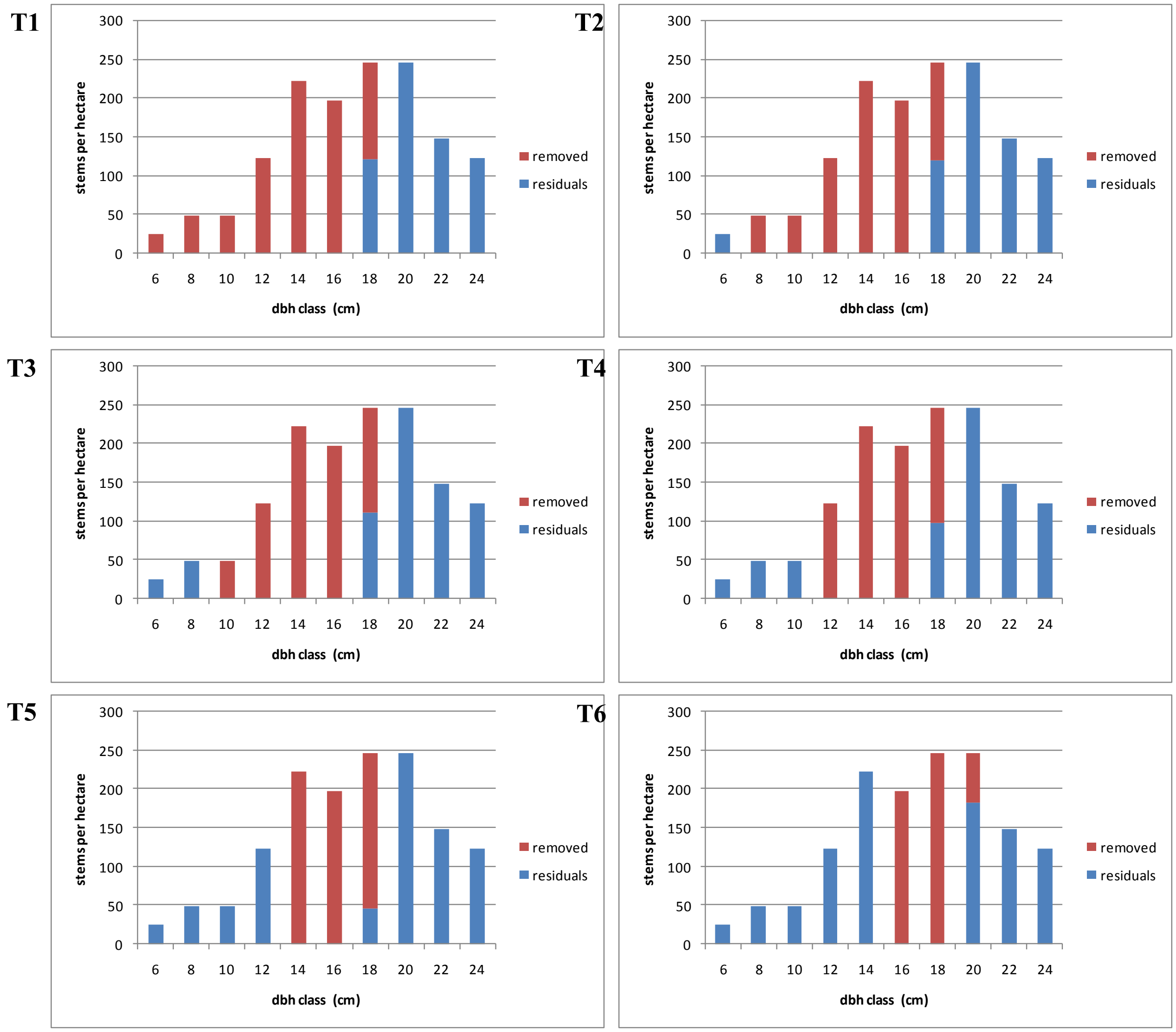

Figure 2: Diameter distribution of stems removed and of the residual stand for thinning types T1 to T6. T1 - thinning from below; T2 - thinning from below starting at dbh > 6 cm; T3 - thinning from below starting at dbh > 8 cm; T4 - thinning from below starting at dbh > 10 cm; T5 - thinning from below starting at dbh > 12 cm; T6 - thinning from below starting at dbh > 14 cm.

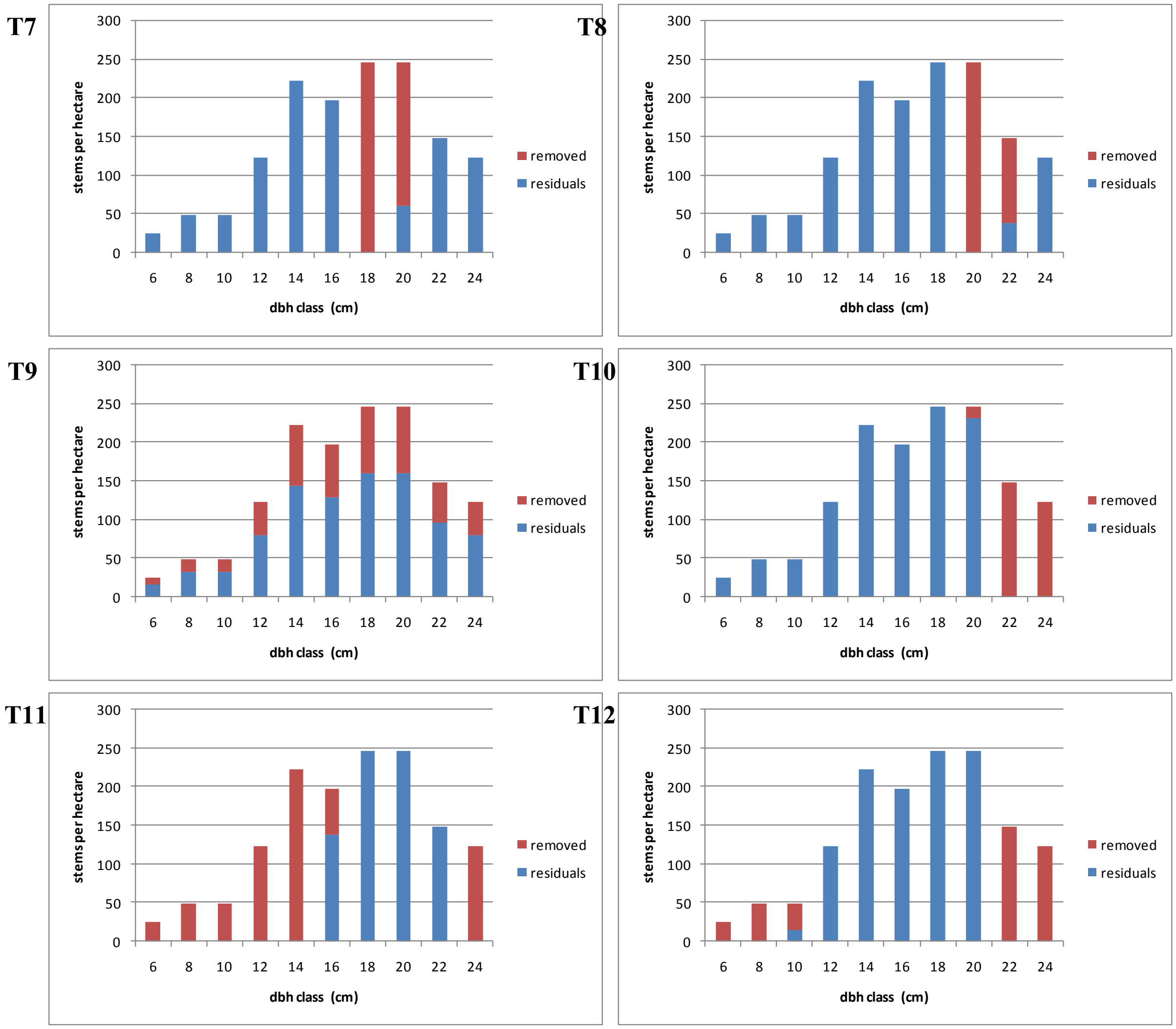

Figure 3: Diameter distribution of stems removed and of the residual stand for thinning types T7 to T12. T7 - thinning from below starting at dbh > 16; T8 - thinning from below starting at dbh > 18 cm; T9 - neutral thinning; T10 - thinning from above; T11 - thinning removing all trees > 22 cm then rest from below; T12 - thinning removing all trees > 20 cm then rest from below

INFLUENCE OF WOOD VALUE ON VARIABILITY OF PROFITABILITY

The difference in overall stand profitability between the 12 types of thinning appeared to be directly related to the change of wood value that trees are subjected to until the end of the rotation. In other words, profit-size relationships that have a steep slope and/or stands that have a longer rotation age have a greater chance to exhibit a large difference among thinning types. By extension, selecting the proper type of thinning is more important in stands that have a wide stem size distribution since they have a greater range of wood value that can be taken advantage of.

Results showed that no thinning type was always the most or the least profitable (Table 1). Almost every type of thinning proved to be the most profitable one in some scenarios and, the least profitable in others, except for the neutral thinning (T9) which was never observed to be the most profitable or the least profitable. In other words, neutral thinning is always suboptimal, but never the worst either.

Table 1: Frequency of profitability ranking observed for each type of thinning.

		Profitability ranking [1,2]											
Type of thinning[3]	null[4]	1	2	3	4	5	6	7	8	9	10	11	12
T1	8	122		3	2		7	1	7	5	2	6	3
T2	8	11	113		3	2		7	1	7	5	3	6
T3	8	13		112	1		5	3	6	3	7	5	3
T4	8	13			112	1	4	4	1	10	4	3	6
T5	8	15				108	7		8	7	4	5	4
T6	8	7			2		101	30	3	1	1	8	5
T7	8	8		1	3	2	12	85	10	21	9	2	5
T8	8	8		14	6	3			5	6	93	16	7
T9	8				8	15		6	50	78	1		
T10	8	16	14	3		3				2	3	13	104
T11	8	5	1	9	6	9	17	16	64	17	11	3	
T12	8	15	13					1	1	8	25	95	

[1] "1" represents the most profitable type.

[2] Columns do not always add up to 158 scenarios for a given rank since some ranks were sometimes tied by two or more types.

[3] See Figures 5.1 and 5.2 for description of each type of thinning.

[4] "null" indicates scenarios where no particular type of thinning was more profitable.

In the 166 wood value scenarios considered, thinning from below (T1) was found most frequently to be the most profitable type while thinning from above (T10) was the type found to be most often the least profitable (table 1). On the other hand, results indicated that when thinning from below (T1) was the most profitable type, thinning from above (T10) was not necessarily the least profitable. Analysis showed that this tendency for thinning from below to be the most profitable was caused in part by assumptions made to keep the scenarios simple but, more importantly by a high number of profit-size relationships having a positive slope, which was found to be a determinant of optimal type of thinning.

CHARACTERISTICS CONTRIBUTING TO A TYPE OF THINNING BEING MORE OR LESS PROFITABLE THAN ANOTHER

For each type of thinning and wood value combination, plots such as those in Figure 4 were generated and used to facilitate the identification of characteristics contributing to a type of thinning being more or less profitable than another.

Analysis of results revealed five conditions most prominent when a type of thinning was the most profitable and, the opposite characteristics when a type was the least profitable:

- thinning removed trees that had already reached maximum or near maximum wood value;
- thinning left trees that would show the greatest increase in wood value when the stand is left unthinned;
- thinning left trees that, at rotation age when the stand is left unthinned, would have been short of a large increase in value (step change);
- thinning left trees that, at rotation age when the stand is left unthinned, have a size corresponding to a steeper portion of the profit-size relationship;
- thinning left trees that already had high wood value.

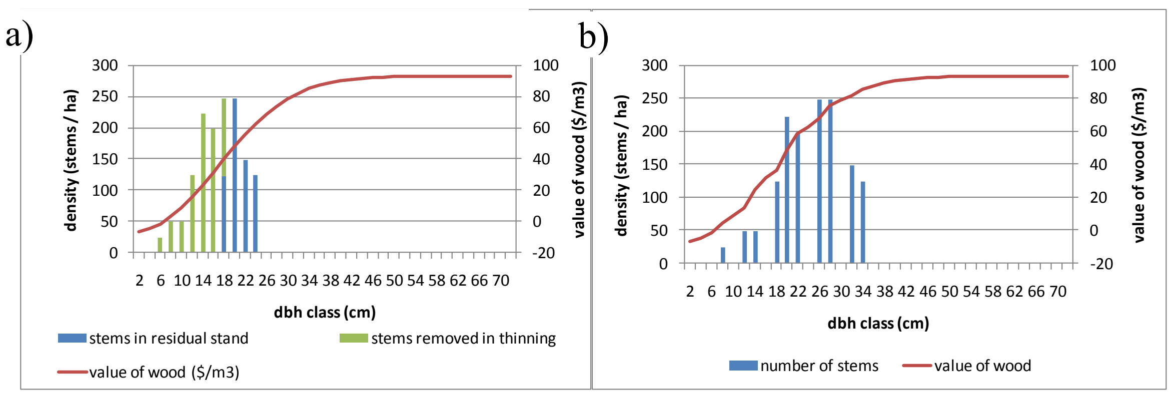

Figure 4: dbh distribution at time of thinning (a) and at rotation age if left unthinned (b), with overlapping profit-size relationship for scenario #24.

The analysis suggests that, at low discount rates (3%), linear profit-size relationships have a simple influence on optimal type of thinning.

- A positive slope of the profit-size relationship indicates that growth on larger trees is more valuable, hence favors thinning from below as much as possible, even at a cost. A greater slope increases the difference in profitability between types of thinning because of the greater difference in wood value of trees of different sizes.
- A null slope of the profit-size relationship indicates that there are no benefits of concentrating growth on any class size. Nonetheless, thinning can still be a profitable venture if it can provide early profits.

- A negative slope of profit-size relationship indicates that growth on larger trees is less valuable, hence greatly favors concentration of growth on the smallest trees. Harvest of the largest trees will prevent an overall decrease in value of the trees.

The influence of more complex forms of profit-size relationships on relative profitability of different types of thinning can also be identified but it requires that the unthinned stands' size distributions at time of rotation be taken into account in order to assess its meaning. In short, since rotation age represents the time when a stand's value growth no longer exceeds the alternative rate of return, a thinning treatment that removes the worst performers at rotation time and concentrates their growth potential on those of highest value increment will usually perform best.

In the presence of a step change in the profit-size relationship, considering the profit-size relationship in combination with the expected size distribution of the unthinned stand at final harvest showed clear benefits. One can identify which tree sizes would reach the step change by themselves at rotation age (i.e. this indicates tree sizes that should not be removed during thinning). It also becomes possible to identify tree sizes that fall short of a large increase in value.

A limited number of simulations were also performed with discount rates other than 3% to explore the sensitivity of our observations. Results seemed to indicate the same tendencies when using a discount rate of 0%. On the other hand, when discount rate was set at 6 and 10%, the results became more inconsistent. At higher discount rate, the early return function of thinning greatly complicates matters and no general interpretations of profit-size relationships could be made.

DISCUSSION

Price (1985) described the importance of wood value when selecting type of thinning when he said

> «*bigger trees command a higher price per cubic meter; therefore volume increment is most lucrative if concentrated on the trees which are already the largest. (...) This argument, however, neglects one crucial factor: volume added to a large tree, while itself commanding a high price, does little to enhance the price per cubic meter of the tree to which it is added. This follows from the form of the price-size relationship, since the largest trees gain almost nothing in unit price from the increase of their size.*»
> Price (1989, p.148)

completed the idea by stating that

> «*there may be a case for retaining the smallest trees in the crop so that their value may be enhanced, rather than taking them out as low-value thinnings*».

Results from our work clarify the influence of wood value on the relative profitability of different types of thinning. Observations made are in line with the work of Price (1985). The general understanding that profitable thinning regimes often consist of thinning youngest stands from below with a gradual shift to a thinning from above in older stands (Price 1989) is appropriate when profit-size relationships follow a logarithmic form such as shown in the example of Figure 4. This form is common to many regions, but it is important to realize that it can vary greatly when wood value is determined by the landowner's specific stand and context (for example, the location of a stand relative to the different mills can significantly change the profit-size relationship).

The fact that thinning from below was frequently the most profitable thinning type should not be taken as a suggestion that it is a better type of thinning than others. The optimal type of thinning is highly dependent on the profit-size relationships considered, and, as such, the type of thinning should be determined based on the actual context of a landowner. Considering the landowner's specific profit-size relationship with the stand's dbh distribution (initial and at final harvest if unthinned) will indicate which trees to remove in priority and which to leave standing, hence indicating the optimal type of thinning. The reason for thinning from below being the best type more often than others in this study is the result of similarities in the profit-size relationships considered. Many profit-size relationships considered in this study showed to have a similar, somewhat constant, positive slope along the determinant range of stem sizes, which favors a form of thinning from below.

Identifying characteristics explaining relative profitability of the different types was relatively easy to do. However, using the characteristics identified in this study to predict relative profitability of different types of thinning can, in some cases, be very difficult, if not impossible. The difficulty comes when there is an apparent balance of good and bad characteristics in the different size classes making the choice of stem size to harvest much less obvious. The good news is that whenever the balance of arguments makes the identification of optimal type very difficult, differences in profitability between the different types are smaller. This reduces the impact of selecting the next best type instead of the optimal one. Preliminary results showed the balance of arguments to become increasingly complex with increasing discount rates. Since the bulk of analyses performed in this work is limited to a discount rate of 3% with limited investigation based on other rates, caution should be taken when using different discount rates.

The results of this study are based on many assumptions. We assumed that thinning treatments had no influence on volume growth of residual stands. If thinning reduces growth due to the inability of a stand to capture all available growing space, the choice of the optimal type of thinning would become even more important to ensure profitability. On the other hand, changes in the ability of different stem sizes to capture available growing space could have important implications. For example, if smaller stems are not able to respond to a thinning harvest, then it would become important to disregard types of thinning whose profitability would depend on an increase in growth rate of those trees.

In the same way that different tree sizes may show different growth responses to thinning, mortality may affect certain stem sizes more than others. This study did not look at the influence of mortality on the optimal type of thinning. The influence of this assumption should be the subject of subsequent studies because of its importance in stand evolution.

All types of thinning were assumed to have the same profit-size relationship. This does not mean that applying different types of thinning will result in the same stand value; rather it means that a tree of a given size, whether it's harvested during a thinning from below or during a thinning from above, will have the same net value. This is likely true when the layout is the same. On the other hand, if a neutral thinning (T9) is performed by removing strips instead of by selection within a stand, then the thinning costs of that given size tree may be reduced compared to other types of thinning. This study did not investigate how to consider simultaneously different types of thinning having different profit-size relationships.

Another major assumption is that wood value is well represented by the function of stem size. If the stand contains trees which wood value greatly depends on factors other than stem size, such as the presence of certain defects, it may be necessary to consider multiple profit-size relationships.

CONCLUSION

The financially optimal type of thinning should be expected to vary from stand to stand. No single type of thinning is always the most or the least profitable, although removing an equal proportion of trees across all sizes (neutral thinning, selection thinning) always proved to be suboptimal. Wood value presented in the form of a profit-size relationship provides information on the contribution of different tree sizes to a stand's overall profitability. Taking into account wood value provides an opportunity to improve overall thinning profitability because it provides an indication of most appropriate trees to remove.

At low discount rates, results suggest that the focus of the thinning should be on identifying tree sizes upon which growth should be favored (trees to be left in stand) rather than on trees to be removed. In other words, with regard to type of thinning, what is left in a stand has a greater influence on profitability than what is taken out. Identification of the best recipients of growth can be done with reasonable accuracy by considering the profit-size relationships in conjunction with expected size distributions at rotation age if left unthinned. Growth should be concentrated on trees that show a large potential for increase in value without thinning and on those that fall short of a large potential increase in value. At higher discount rates, the early return function of thinning greatly complicates matters and no simple solution was found.

Further work is required to determine the influence of relaxing some of the assumptions made and to identify how this knowledge could be efficiently used to improve the selection of more profitable thinning regimes.

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A SCOR-BASED FRAMEWORK TO PORTRAY WOOD SUPPLY SYSTEMS – PRELIMINARY RESULTS FROM THE UNITED-STATES, FRANCE AND CHILE

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ABSTRACT

The work presented in this paper is a work package within the FlexWood project. It aims to develop a framework to describe, in a generic way, any wood supply systems (WSS) and enables some comparisons. In this paper, we provide a general description of this framework consisting of five main components (environment, strategy, structure, enablers and performance) and partly based on a forestry adaptation of the Supply Chain Operations Reference (SCOR) model. Preliminary results of the framework application are presented for the WSS of three countries (USA, France and Chile). The focus is on the decoupling point (i.e. the boundary between forecast driven and order driven planning) and the customization options in the cases studied. Ten locations of the decoupling point have been identified.

Keywords: Wood supply system, decoupling point, customization options, contingency theory, SCOR model

INTRODUCTION

The FlexWood (Flexible Wood Supply Chain) project is a major European Union funded research initiative. It uses the assumption that wood supply chains in the forest products industry are not able to make full use of the real value of raw materials. The objective of FlexWood is therefore to build a novel logistics wood supply system (WSS) that increases value recovery along the wood supply chain. This "FlexWood WSS" is based on the development and adaptation of logistics concepts that provide better information assessment on wood resources (e.g. aerial and terrestrial laser technologies), enhance optimization models, and increase flexibility and customization capabilities.

The work presented in this paper is a work package within FlexWood. It aims to develop a framework to describe, in a generic way, any WSS and enables some comparisons. The studied WSS spans from the procurement of commercial stands (i.e. both internally from own forestland and externally from purchase) to the delivery at the demand sites (i.e. mills gates, port or train terminal) and includes harvesting, primary and secondary transport and merchandising. WSS are complex system composed of actors, planning and execution processes, coordination mechanisms and information, material and financial flows.

Additional aspects to be addressed within the framework are the agility enablers, the competitive strategy and the customization options of the studied WSS. The results of the framework application on WSS in different countries will support the design of the “FlexWood WSS”.

In Section 1, we introduce the five main components of the proposed framework. Focusing on the location of the decoupling point and the customization options in the WSS studied in three countries (USA, France and Chile), preliminary results of the framework are presented and discussed in Section 2. Concluding remarks are then provided.

PROPOSED FRAMEWORK

To support the description and the development of novel logistics concepts within FlexWood, we propose the utilization of a contingency-based framework. Contingency theory is an organization theory originating at the end of the 1960’s, based on the open systems theory for organizational analysis (Stanley, 1993). Contingency theory has already been used in different studies in supply chain management, emphasizing that success in value creation is dependent on alignment between actions, structure and the external environment, assuming that there is no universal set of choices that is optimal for all businesses (Daft and Armstrong, 2009).

Combined to recent studies and frameworks on manufacturing and supply chain agility (e.g. Sharifi and Zhang, 1999; Lin et al., 2006; Baramichai et al., 2007), we propose to study and explain the match between external environment factors and the structure of a supply chain through the business and supply chain strategies, as well as specific enablers. A sustainable and competitive performance level of a supply chain is therefore contingent on its external environment through adequate choices of business and supply chain strategies, agility enablers and a supply chain structure. These descriptive elements are structured in five main components in the proposed framework (see Figure 1). The following subsections introduce the five components of the conceptual framework.

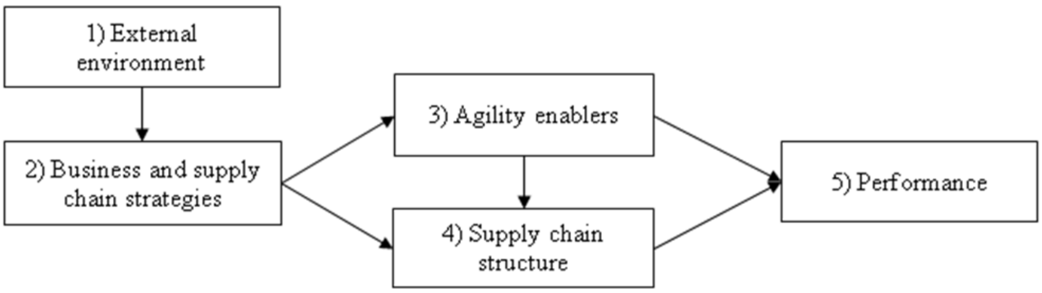


Figure 1: Conceptual framework.

External environment

One of the first and most influential approaches for external environment analysis is Porter’s strategic analysis based on five competitive forces: bargaining power of suppliers, bargaining power of buyers, threat of new entrants, threat of substitute products or services and rivalry among existing firms (Porter, 1985). These forces have been combined with the SCOR model for supply chain analysis by Di Martinelly et al. (2009). An enhanced set of ten forces for environment analyses is presented by Daft and Armstrong (2009): internal industry sector, raw materials, human resources, financial resources, market sector, technology, economic conditions, government, socio-cultural sector and international sector.

A complementary environment analysis is based on its uncertainty, which is a function of the complexity and instability in the aforementioned forces (Daft and Armstrong, 2009). Complexity means the number or heterogeneity of elements relevant to an organization's operations while instability means that some environmental forces shift abruptly and unexpectedly in a short time period (i.e. a matter of days in WSS). The greater the degree of environment uncertainty is, the greater the needs to develop an agile supply chain are, in order to be able to forecast, detect and react quickly and effectively to changes (Christopher, 2000).

By adding climatic considerations to the aforementioned forces, an external environment analysis based on eleven forces and their respective level of uncertainty makes it possible to specify objectively which are: i) the main drivers for agility and ii) the supply chain processes (see 1.4) impacted by the environment uncertainty.

Business and supply chain strategies

Competitive strategy addresses "how an organisation chooses to compete in a market, particularly the issue of positioning the company relative to competitors with the aim of establishing a profitable and sustainable position" (Hallgren and Olhager, 2006). Distinguishing among three major strategies for competitiveness (i.e. cost leadership, differentiation, and focus), the typology for competitive strategy of a company by Porter (1985) is probably the most well-known typology. Cost-leadership means that the company takes the competition head on, offering a product that is equivalent to those offered by competitors, but more efficiently (e.g. cheaper price). The differentiation is to avoid direct competition by differentiating the products and/or services offered to deliver higher customer value, making it possible to charge a premium price. The focus strategy is to target one or more market segments of the company's markets and apply one of the previous strategies in each targeted market segment.

Once the business strategy is defined, it is time to define the supply chain strategy, or how the supply chain processes shall be structured and coordinated to support the company in achieving its business strategies. From a value creation network perspective, the issue is to determine which of the processes should be executed and/or controlled by the organization, and which ones should be made by another enterprise. This is summarized by the strategic options of making, not making, outsourcing or making with someone else (D'Amours et al., 2010).

Agility enablers

The concept of organizational and manufacturing agility originated in the mid 1990's and has started to be spread and adapted to the supply chain field since the end of the 1990's (Li et al., 2008). Supply chain agility is composed of four dimensions: customer sensitiveness, information drivers, process integration and network integration (Christopher, 2000). Enablers, including best-practices, within these dimensions are specific to each industry or sector studied and therefore need to be contextualized and adapted. Moreover, the enablers make the linkage between the business strategy and the supply chain structure. The utilization of the adequate enablers supports companies in the WSS in achieving their business objectives by “preparing, maintaining, and managing information and relationships upon which planning, sourcing, making and delivering execution processes rely on” (SCC, 2008).

To evaluate the level of acquisition of these enablers by a specific WSS, a four-level scale based on the competence management theory is proposed (Drejer, 2001; St-Amant and Renard, 2006). With this evaluation approach of supply chain agility enablers, it is possible to evaluate the level of agility of a WSS by supply chain process (see 1.4) and by agility dimension.

Supply chain structure

Due to its detailed description of the supply chain processes and their coordination (i.e. inputs and outputs), the SCOR model by the Supply Chain Council was chosen to describe WSS. Moreover, a promising first attempt of the SCOR model adaptation in WSS was made by Schnetzler et al. (2009). The SCOR model has been developed to describe the business activities associated with all phases of satisfying a customer’s demand and is organized around five process types: Plan, Source, Make, Deliver and Return (SCC, 2008). For the description of the WSS, only the first four processes will be used (i.e. no Return).

In addition to the planning and execution processes, another important concept to include in the description of a supply chain is the decoupling point. Wikner and Rudberg (2005) define it as “the point in the flow of goods where forecast-driven production and customer order-driven production are separated” or, in other words by Rudberg and Wikner (2004), “the point in the value-adding material flow that separates decisions made under uncertainty from decisions made under certainty concerning customer demand (…)”. Four typologies of decoupling point are traditionally defined: engineer-to-order, make-to-order, assemble-to-order and make-to-stock.

The decoupling point is sometimes referred to as the order penetration point (Wikner and Rudberg, 2005). It can also be referred to as the postponement point or where the product is differentiated, with alternative customization options (Poulin et al., 2006). This latter concept of customization refers to the design of offers to the market, including the corresponding manufacturing or service capacities, based on a targeted segmentation of customers. As quoted from Montreuil and Poulin (2005), the goal with customization “is to gradually develop the competitiveness of the firm by having an offer that closely matches the evolving personalized expectations of customers in the targeted segments and by having the capability to profitably deliver the offer on a reliable basis”.

Performance

There is a scarce literature on supply chain performance measurement applied to WSS. The publications are mainly on performance measurement system dedicated to a fraction of the WSS (e.g. harvesting) and where the focus is on production metrics such as ‘cubic metre per productive hour’ or ‘utilisation rate’ (Drolet and LeBel, 2009). Recently, a computerized decision-support tool, ToSIA, has been proposed to measure the sustainability of an entire forest products industry chain, i.e. from forest regeneration to the end-of-life of forest products (Lindner et al., 2010). In the proposed framework, the first performance measures of the WSS are the agility evaluation in section 1.3 and the customisation capabilities (i.e. the customisation options offered to the wood customers).

PRELIMINARY RESULTS

Between August 2010 and March 2011, study stays in Southeastern USA (Alabama, Georgia and Mississippi), France (region of Aquitaine) and Chile (regions around Concepcion and Valdivia) lead to a total of 42 semi-structured interviews within 39 distinct organizations from the private and public sectors. Several WSS based on plantation of pines were studied in each country, specifically: full-tree harvesting method in Southern yellow pines (e.g. loblolly) plantation in US, cut-to-length harvesting method in maritime pine plantation in France and full-tree harvesting method in radiata pine plantation in Chile. Among these WSS, three main customization options (see Table 1) and ten locations of the decoupling point (see Table 2) were identified.

Table 1: Definition of the customization options

Customization options	Definition
Standard assortment	Product produced strictly to forecast and thus kept in inventory by the wood supplier.
Catalogue assortment	Products ordered by the wood customer from a list of available specifications provided by the wood supplier. These products are not kept in inventory and produced to order by the wood supplier. Note: the specifications of a standard assortment are included in the list of available specifications for a catalogue assortment.
Custom assortment	Product never produced before following new specifications (i.e. not included in the list of available specifications for a catalogue assortment). Designed by the wood supplier according to the requirements from a wood customer.

Table 2: List of the decoupling point locations

	Country		
Decoupling point location	**Usa**	**France**	**Chile**
Buy block-to-order	X	X	X
Start block harvesting-to-order	X	X	X
Adjust bucking pattern-to-order (in the block)		X	
Primary transport-to-order		X	
Felling specific tree-to-order & Primary transport-to-order	X		
Adjust bucking pattern-to-order (roadside)	X		X
Secondary transport-to-order (roadside)	X	X	X
Secondary transport-to-order (intermediate wood yard)		X	
Bucking-to-order (bucking plant)			X
Wood yard transport-to-order (on-site yard)		X	X

Adopting a representation inspired by Poulin *et al.* (2006), Figures 2 to 4 illustrate how the decoupling points relate to the main processes involved in the material flow in the WSS studied in each country. For instance, in Figure 2, the decoupling point can be at six different locations from “Buy block-to-order” at the extreme left (forest side) to “Secondary transport-to-order” at the extreme right (wood customer side). All activities to the right of the decoupling points are linked to the demand of a wood customer (order driven). The activities prior to the decoupling points are made according to forecast of demand (forecast driven).

Symbolized by a rectangle, the customization options offered to the wood customers in the WSS studied in each country are illustrated at the top of Figures 2 to 4. A dotted arrow links the customization options to each process receiving the customer orders. For instance, in Figure 2, with the “standard assortment” option, there is only one decoupling point possibility, leading to only one process as order driven (Deliver-Secondary transport) and the five others are forecast driven. For the “catalogue assortment” option, there are five different possibilities for the decoupling point and two possibilities for the “custom assortment” option.

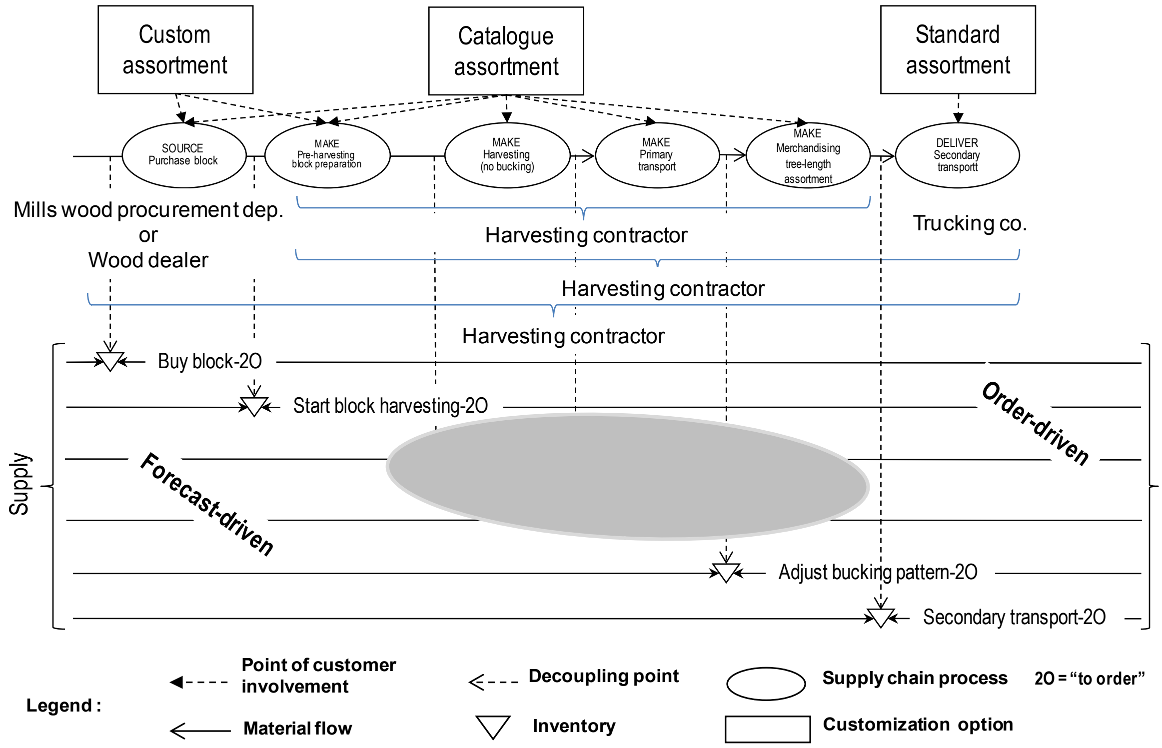


Figure 2: Decoupling points and customization options in the WSS in USA.

Table 3: Process-actor configurations in three WSS (USA, France and Chile).

		Actor						
Process		Bucking plant at the mill	Cooperatives	Harvesting contractor	Mills wood procurement department	Stocking yard at the mill	Trucking company	Wood dealer
Source	Purchase block		F3	U4, F4	U2, U3, F1, F2, C1, C2			U1
Make	Pre-harvesting block preparation			U1, U2, U3, U4, F1, F2, F3, F4, C1, C2	F2			
	Harvesting			F1, F2, F3, F4	F2			
	Harvesting (no bucking)			U1, U2, U3, U4, C1, C2				
	Primary transport			U1, U2, U3, U4, F1, F2, F3, F4, C1, C2	F2			
	Merchandising tree-length assortment			U1, U2, U3, U4, C2				
	Merchandising log assortment	C2		C1				
Deliver	Secondary transport			U1, U3, U4,	F2		U2, F1, F2, F3, F4, C1, C2	
	Loader transport	C2				F1		F1

Legend: *n* = {1,2,...} U*n* = scenarios in USA F*n* = scenarios in France C*n* = scenarios in Chile

Figure 3: Decoupling points and customization options in the WSS in France.

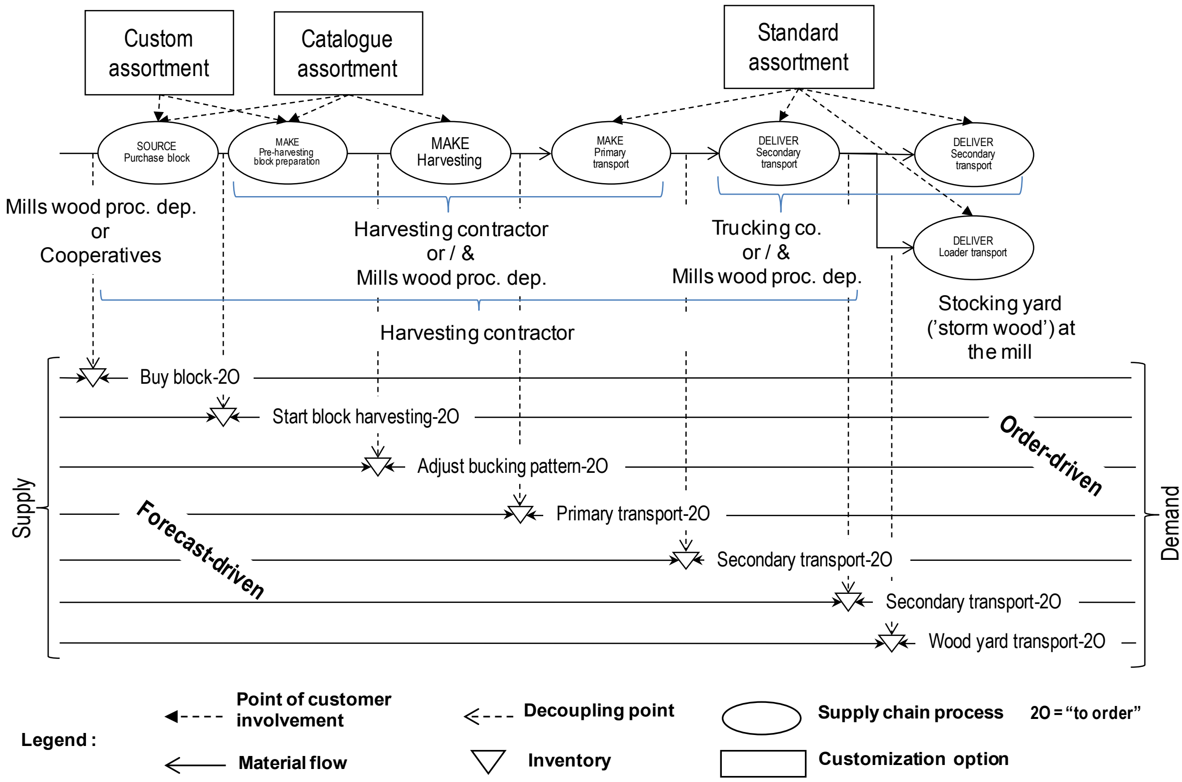
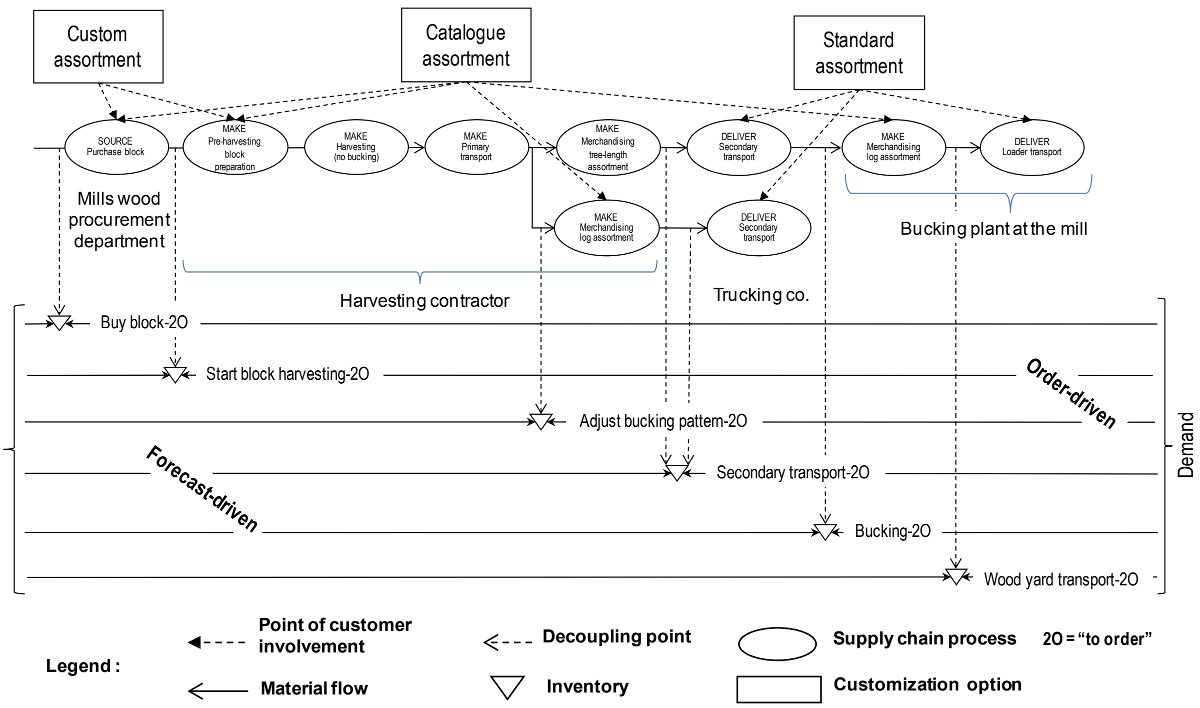


Figure 4: Decoupling points and customization options in the WSS in Chile.



CONCLUSION

The paper introduced the five components of a framework to describe, in a generic way, any WSS and enables some comparisons (e.g. agility). Using this framework in the study of WSS in three countries, ten locations of decoupling point, three main customization options and nine process-actor allocation scenarios were identified and presented. Our results indicate that using the contingency theory along with Porter's organization theory to complement the SCOR model provides a conceptual framework well adapted to describe WSS. The next steps include, for the three countries studied, a better description of the external environments, the agility enablers utilized and the performance levels achieved. Future research directions include the improvement of the framework and its validation on actual cases of WSS as well as on additional cases from three other countries (Canada, Poland and Sweden).

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POTENTIALS OF POSSIBLE MACHINE SYSTEMS FOR DIRECTLY LOADING LOGS IN CUT-TO-LENGTH HARVESTING

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ABSTRACT

In conventional ground based mechanized cut-to-length systems a harvester fells and cuts trees into logs that are stored on the ground until a forwarder picks them up and carries them to landing sites. A proposed improvement is to place logs directly into the load spaces of transporting machines as they are cut. Such integrated loading could result in cost reductions, shorter lead times from stump to landing, cleaner logs and lower fuel consumption. However, it might also create waiting times for the machines involved, whereas multifunctional machines are likely to be expensive. Thus, it is important to analyze whether or not the advantages of any changes outweigh the disadvantages. The conventional system was compared with four potential systems, including two with autonomous forwarders, using discrete event simulation with stochastic elements in which harvests of more than 1000 final felling stands (containing in total 1.6 million m^3) were simulated 35 times per system. The results indicate that harwarders have substantial potential, and may become competitive if key innovations are developed. Systems with co-operating machines have considerably less potential, limited to very specific stand conditions. The results conform with expected difficulties in integrating processing and transporting machines' work in variable environments.

Keywords: Integration, harvester, forwarder, harwarder, Beast, simulation

Note: This proceeding contribution is a summary of a manuscript that at the time for the conference was under review for publication with a scientific journal. Please contact the authors for reference to the full article.

INTRODUCTION

In the conventional mechanized cut-to-length (CTL) system a harvester fells and cuts trees into logs that are stored on the ground until a forwarder picks them up and carries them to landing sites. A proposed improvement is to place logs in the load space of the transporting machine as they are cut. Besides possible cost reductions, integrated loading should also result in shorter lead times from stump to landing, in cleaner logs and lower fuel consumption. In this paper four potential systems for future CTL harvesting are considered:

• Harwarder; a manned machine does the work of both harvester and forwarder.

• Autonomous load-changing (ALC) system; a harwarder load logs directly into its bunk. When full, the bunk is switched with the systems' autonomous forwarder, which transports, unloads and returns it.

• Autonomous direct-loading (ADL) system; a harvester cuts and processes trees directly into the bunk of one of the system's two autonomous forwarders that transports and unload automatically.

• Remote-controlled direct-loading (RDL) system In principle, the same as the ADL system outlined above, but with two manned forwarders taking turns to remotely control one unmanned harvester (as in the Besten system (e.g. Bergkvist 2006)).

When referring to methodology in which harvesters load directly into forwarder bunks in ADL and RDL, these two systems will here be called Integrated Forwarder Loading (IFL) (cf. Lindroos (2011)).

Integration of work elements might create waiting and blocking times for the machines involved, whereas multifunctional machines are likely to be expensive. Thus, it is important to analyze whether or not the advantages of considered options outweigh the disadvantages. This can be done by applying theoretical comparisons, in which idealized suggested systems are analyzed to estimate their maximal potential. However, since machine interactions are likely to create queuing, the analysis would benefit from dynamic and stochastic approaches to fully evaluate the potential of different systems. The objective of this study was to evaluate the potential of possible future systems for CTL harvests by: i) building a discrete event simulator to capture the dynamic and random character of interactions between machines used for integrated loading of logs, ii) comparing the economic performance of four potential systems for integrated CTL harvesting and a conventional harvester-forwarder system in final felling.

MATERIAL AND METHODS

To fully evaluate the impact of the analyzed work methods, a discrete-event simulator was implemented in Matlab to simulate the time consumptions of the involved machines. Two general assumptions are made concerning the similarity of the five investigated systems. First, the outcomes of all systems' work are assumed to be equal, in terms of both output quality and impact on the stand environment (e.g. rutting). Second, it is assumed that the same type of work is done equally rapidly by all systems. Hence, the potential of integrated loading as a work method is addressed without considering possible differences in specific technical implementations between systems. This is justified by the fact that if technical advances make one system faster than another (e.g. by use of a stronger crane), those advances could also be applied to other systems, unless there are fundamental restrictions (e.g. being enabled due to the lack of operator). The following factors were considered crucial to implement in a dynamic manner to make the simulations realistic and relevant:

1. Random delay occurrence and duration during work, due to e.g. machine breakdowns and operator needs.

2. Variation in forwarding distance within stands, since the distance depends on where in a stand a load is collected, which affects the occurrence of queuing and waiting times.

3. Queuing due to random delays and mismatches between the work of interdependent machines. For instance, a harvester may have to wait for a forwarder to be available before loading or switching of loads can commence in the IFL and ALC systems, respectively.

To avoid the simulator being too complex, other parts were applied in a static and deterministic manner. The simulator was applied to data from more than 1000 Swedish final felling stands (containing in total 1.6 million m^3), and each simulation was repeated 35 times to allow for random delay effects. The computations for time consumptions, costs and fuel consumptions were based on Nurminen et al. (2009); Nurminen et al. (2006) and Lindroos (2011).

RESULTS AND CONCLUSIONS

Based on the conducted simulation it can be concluded that harwarders have considerable theoretical potential to compete with the conventional system under most of the tested stand conditions, and quite minor technical innovations appear to be required to realize the system's potential. The other tested systems had, if any, potentials under very specific stand conditions, making them viable only as complements to the conventional system. For the ADL system the situation is the opposite to that of the harwarder, having low potential due to a combination of limitations in its work organization and the technical challenges associated with autonomizing machines. A prototype RDL system (Besten) is already available, but the system suffers from the limitations in its work organization and high system costs. The ALC system represents a compromise between the harwarder and IFL systems, in terms of being less limited by the work organization but requiring autonomous forwarders to be viable.

This study indicates that future focus should be on developing harwarders when aiming for direct loading of logs in mechanized CTL operations. When the ongoing development towards autonomous forwarders (e.g. Ringdahl et al. (in press)) results in machines available on the market, they should be used either in the conventional system or with a load-changing harwarder, but not with a direct-loading harvester.

As the possible integrated loading systems emerge further, future analysis could focus on mimicking the specific characteristics and limitations of the suggested innovations. Hence, expected potentials when they are introduced could be estimated instead of the theoretical maximal potentials addressed here.

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A REVIEW OF SKIDDING DISTANCES METHOD UNDER VARIABLE RETENTION HARVESTING CONSIDERATIONS

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ABSTRACT

Skidding distances in forest operations have rarely been questioned and the traditional method proposed by Matthews (1942) continues to be generally applied. We propose a modification to this method which integrates variable retention harvesting considerations, specifically volume heterogeneity and obstacles, to determine skidding distances and costs. These spatial and structural elements associated with partial cutting can be very complex, depending on the objectives of retention. In this study skidding distances, volume distribution and harvesting costs were analyzed. First, skidding distances were estimated and compared using three methods: a) tracking skid trails on aerial photos after harvest, b) a GIS raster procedure and c) the traditional method. Results were comparable, but the raster procedure was most efficient for integrating the distribution of variable volume to be harvested. We then included the volume distribution in harvest blocks (values obtained from permanent sample plots) using two assignment methods: a) photo interpretation and b) Thiessen interpolation, to obtain volume weighted by area of influence. Our results show no significant difference between the assignment methods. Third, the raster procedure and Thiessen volume assignment were combined to adjust skidding distances to take into account the shape and volume distribution in harvest blocks. We conclude that, because this combined analysis is highly sensitive to changes in volume distribution and harvest rates, it is useful for estimating skidding and harvesting costs and permits explicit incorporation of spatial considerations (shape, size and volume) of variable retention in forest planning.

Keywords: Skidding distance, harvest cost, variable retention cutting, spatial simulation.

INTRODUCTION

Clear cutting represents a major driver on the managed landscape and careful logging to preserve advance growth (CPRS) is the dominant method in Quebec. However, it is not adapted to all forest stands (MNR, 2003). Partial cutting (PC) refers to a gradient of cuts such as commercial thinning, selection cutting, shelter wood cutting and partial retention cut. Partial cutting seeks different objectives, ex.: removing the diseased stems (MNR, 2003), maintaining key habitat elements for several species (Drapeau et al., 2003, Courtois, 2003), maintaining floristic elements (Fenton, 2005) and, in some cases shortening rotation length (MRN, 2003).

These silvicultural treatments include not only the partial removal of woods, but also the preservation of structural elements in the landscape: the case of variable retention cutting (CRV).

Variable retention cutting is the maintenance for at least one complete rotation of structural elements specific to the stand harvested as forest patches, live trees, snags, woody debris or the thickness of forest floor or understory species - stage (Pentassuglia, 2003). Partial cutting produces long-term benefits and are accepted by the public (Hassler and Grushecky, 2000). Indeed, considering the current forestry context, partial cutting and variable retention become very interesting alternatives to the CPRS. From the ecological point of view, several studies have demonstrated that biodiversity in harvested areas has a positive relationship with the number of structural elements used (Sougavinski and Doyon, 2002). Thus, the PC and CRV could potentially help reduce the effect of stock shortage of mature timber. But, PC is not a common practice in the boreal forest because it is more expensive to implement than CPRS. Adapted machinery is needed, operators must be specially trained, the planning process is complex and more access roads are required (Pentassuglia et Meek, 2004) and lower harvest volume per hectare (Meek et Simard, 2000). However, Holmes et al. (2010) showed that the volume of timber extracted per unit of effort (productivity) may be higher in riparian zones (partial section) than in clearcuts. This means that partial cutting treatments could be more feasible when it is properly planned.

The models used to estimate harvesting costs are generally based on total harvest cutting while skidding distance has rarely been questioned and thus, the traditional method proposed by Matthews (1942) continues to be applied. However, when a harvest incorporates elements of retention, the variable distribution volume in a harvest block and the costs of skidding, estimated harvest costs may incorporate large bias. Most of the known productivity models that estimate harvest costs use statistical models that generate local functions for different equipments. The commonly used variables are skidding distance, the amount of trees to be cut and the volume per stem (Tufts, 1997). These productivity models consider that the trees to be cut are distributed homogeneously within the harvest block. However, corrections must be made when considering structural obstacles during harvest operations and volume heterogeneity. These obstacles may include variable patches of residual trees or individual trees left over after harvesting. These factors may effect the skidding distance and productivity according to proportion and distribution of retention to be maintained and consequently the wood procurement costs.

The overall objective of this project is to propose a model that integrates variable retention harvesting considerations, specifically volume heterogeneity and obstacles, to determine skidding distances and costs. These spatial and structural elements associated with partial cutting can be very complex, depending on the objectives of retention.

The specific objectives were to:

- Select an effective method to estimate skidding distance.
- Determine the effects of variable retention harvested volume and volume heterogeneity on the skidding distance.
- Determine the combined effects of skidding distance and variable retention harvesting on skidding cost.
- Propose a model that integrates variable retention harvesting, volume heterogeneity and obstacles on skidding distance.

DATA AND METHODS

This study was carried out in the north-western Quebec boreal forest in the Abitibi clay belt region. We collected information from a study network where silvicultural treatments (careful logging to preserve advance growth (CPRS)), harvesting with protection of small merchantable stems (CPPTM) and variable retention cutting (CRV)) and an unharvested (control) was applied (Bescond et al., 2011). At each site silvicultural treatments were executed on blocks over 29 ha in size. The sites were harvested using a single-grip harvester and forwarder. In the study territory of 1362 ha, five sites (Puiseaux, Collines de Gaudet, Collines de Maskuchi, Fénelon and Dufay) were analysed (figure 1, table 1). This territory is dominated by black spruce (Picea mariana [Mill.] BSP) – feather moss (e.g., Pleurozium schreberi [Brid.] Mitt.) forests, and is particularly prone to paludification between fires due to its poorly drained clay dominated soil. Plots were established at randomly selected points in the stands before harvest.

SKIDDING DISTANCE

The road spacing calculation presented by Matthews (1942) computes the least-cost road and landing spacing by a trade-off between skidding and road construction costs (Nadeau et al., 2002). Various methods have been elaborated, as summarized by Chung et al., (2008), to design efficient forest road networks. In all cases the average skidding distance is an important input in the total cost. In addition, skidding distance is well correlated with machine productivity and cost.

Estimating average skidding distance depends on the different elements: shape of the harvest block, landing configuration or multiple landings along the forest roads. Different solutions have been proposed to estimate skidding distance following the elements cited earlier (See Greulich (2002) for examples).

We evaluated three different approaches to estimate average skidding distance a) the traditional method (equation 1), b) tracking skid trails on aerial photos after harvest (equation 2) and c) a GIS raster procedure (equation 3) (figure 2, table 2). These approaches are compatible with forest harvesting operations in Quebec's boreal forest because they are characterized by the presence of parallel skid trails and aligned perpendicular to the forest road. These skidding trails, that cover less than 25 % of cut area, facilitate the movement of machinery and preserve advance growth (Anonyme, 2006).

Other researchers, including Greulich, also developed formulas incorporating other parameters such as variable volume distribution and obstacles (Contreras and Chung, 2007). Similarly, many models include the location of roads, either by heuristic procedures or the use of available technologies in recent years to optimize, such as ArcGIS ™.

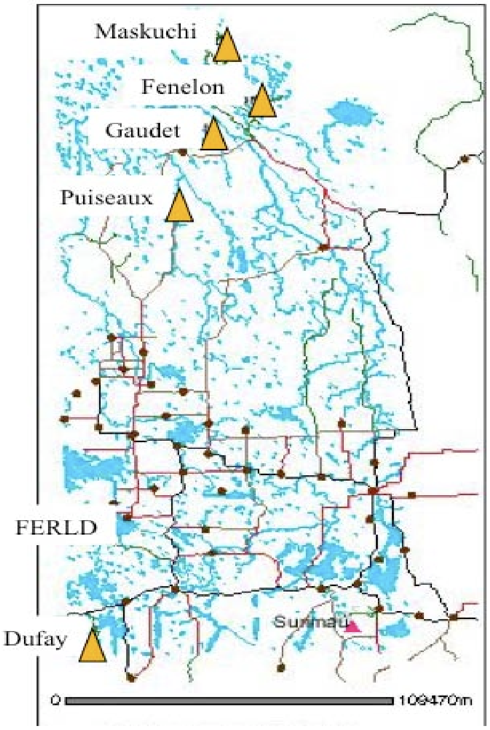

Figure 0: Localisation of study area in the Abitibi clay belt region.

Table 1: Study area description by site, silvicultural treatment, ecological region, area and numbers of available plots.

Site	Ecological region	Treatment	Area (ha)	Plots
Dufay	5a	CPRS	35,03	13
		CPPTM	84,98	13
		Control	29,02	13
Fénelon	6a	CPRS	97,46	14
		CPRV	126,03	18
		control	79,38	18
Gaudet	6a	CPRS	43,11	17
		CPRV	69,23	17
		control	38,15	13
Maskuchi	6a	CPRS	172,78	58
		CPPTM	226,98	104
		control	130,58	34
Puiseaux	6a	CPRS	85,92	19
		CPRV	83,46	17
		control	93,25	18

*Plots : permanents plots.

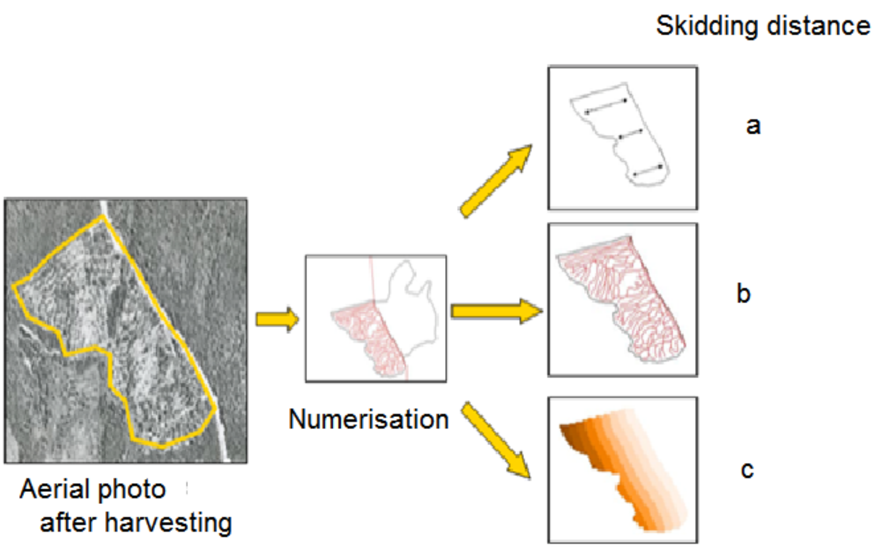

Figure 2: Illustration of three approaches to estimate average skidding distance a) the traditional method, b) tracking skid trails on aerial photos after harvest and c) a GIS raster procedure.

VOLUME ASSIGNMENT

In the absence of forest management (harvest follow by plantation) the natural boreal forest presents a variable distribution of volumes. In fact, the natural boreal forest is rather irregular and uneven, as a result of natural disturbances such as epidemics and forest fires that affect the landscape (Vaillancourt et al., 2008). We then manage the volume distribution in harvest blocks (values obtained from permanent sample plots) using the a) volume average and two assignment methods b) photo interpretation and c) Thiessen interpolation, to obtain volume weighted by area of influence (figure 3). Thiessen interpolation enables the determination of the small harvest units - representing either fixed amounts or characteristics of habitats of interest - (Barrett, 1997), and to describe patterns of volume distribution in forests (Kristensen, 2006) automatically with the help of GIS.

The average volume per hectare obtained from photo-interpretation and those obtained by the Thiessen interpolation, were weighted by the assigned area (Equation 4), and then compared to the average volume from permanent plots - a) traditional method- for each block of harvest (Equation 5).

Table 2: Performed equation to estimate weighted skidding distance

Equation 1	Equation 2	Equation 3	Equation 4	Equation 5	Equation 6
$\overline{D}_A = \frac{D_{\max}}{2}$	$\overline{D}_B = \frac{\sum_{s=1}^{n} D_S}{n}$	$\overline{D}_C = \frac{\sum_{j=1}^{n} D_{i,j}}{n}$	$\overline{V}_{Th-Ph} = \frac{\sum_{j=1}^{m}(V_j \times S_j)}{\sum_{j=1}^{m} S_j}$	$\overline{V}_{Tr} = \frac{\sum_{i=1}^{n} V_i}{n}$	$\overline{D}^c = \frac{\sum_{j=1}^{n}(\frac{V_j}{C_k} \times d_j)}{n}$
Where : $\overline{D}_A$: Average skidding distance (m). *Dmax* : Maximum skidding distance (m).	Where : $\overline{D}_B$: Average skidding distance based on trails visible on aerial photos after harvest (considered as reference) (m). D_s : Distance of skid trail « *s* » (m). *s* : Skid trail id. *n* : Total of skid trail by harvest block.	Where: $\overline{D}_C$:Average Skidding distance (m) $D_{i,j}$: Distance from pixel *i*,*j* to forest road (m) *i*, *j*: Position pixel *n* : Total of pixels by harvest block	Where : $\overline{V}_{Th-Ph}$: weighted average volume per ha assigned by photo interpretation or Thiessen interpolation in a harvest block (m³/ha). V_j : estimated volume per ha in the subsection« j » within a harvest block (m^3/ha). S_j : Area of subsection « j » within a harvest block (ha). j : Subsection Id.	Where : $\overline{V}_{Tr}$: Average volume per ha in a harvest block (m³/ha). V_i : estimated volume per ha for the plot « i » in a harvest block (m^3/ha). n : total number of plots in a harvest block.	Where: $\overline{D}^c$: weighted skidding distance in a harvest block (m). V_j : Estimated volume per ha within a harvest block at the « j » position (m^3). C_k : volume per turn (m^3) of skidding machine « k » (Wheeled skidder, forwarder, etc). d_j: Distance at the « j » position within a harvest block from the road (m). *j* : pixel id within the block. *n* : total number of pixels.

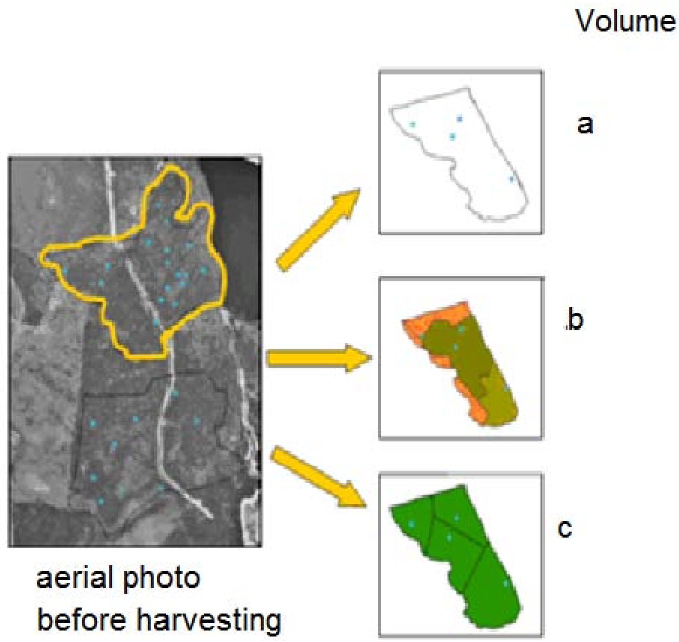

Figure 3: Illustration of average volume per hectare a) traditional method and two assignment methods to obtain volume weighted by area of influence b) photo interpretation and c) Thiessen interpolation.

WEIGHTED SKIDDING DISTANCES

The non-homogeneity distribution of volume in the harvest blocks has been expressed by the two assignment methods. We chose Thiessen interpolation to conduct this analysis because it facilitates computing. The equation 6 take into account skidding distance (obstacles, retention) and weighted average volume within the harvest block.

The ratio (Vj / Ck) in equation 6 represents the number of necessary cycles to haul the wood content on a pixel. This number is set to 1 when the volume to be extracted is smaller than the load capacity. It was assumed that the machine will go to the block position and will travel this distance, even if the load is lower than its capacity. We set 1.5 m^3/turn as load capacity in the analysis. This value was determined by comparing the effects of variation on the skidding distance estimation and taking into account a minimum load capacity. Vj is the value of the volume of the pixel "j" which is determined by multiplying the average volume per hectare in the block or a section of the block times the size of a pixel, in our case 0.01 (pixel size 10 m). A higher pixel size implies taking into account the movements of the machine within a pixel and this element was not considered in this analysis. In addition, the pixel size used (10 m) reflects the separation between skid trails, which is about 20 m in Quebec. Figure 4 illustrates an example of the procedure applied to compute the weighted skidding distance.

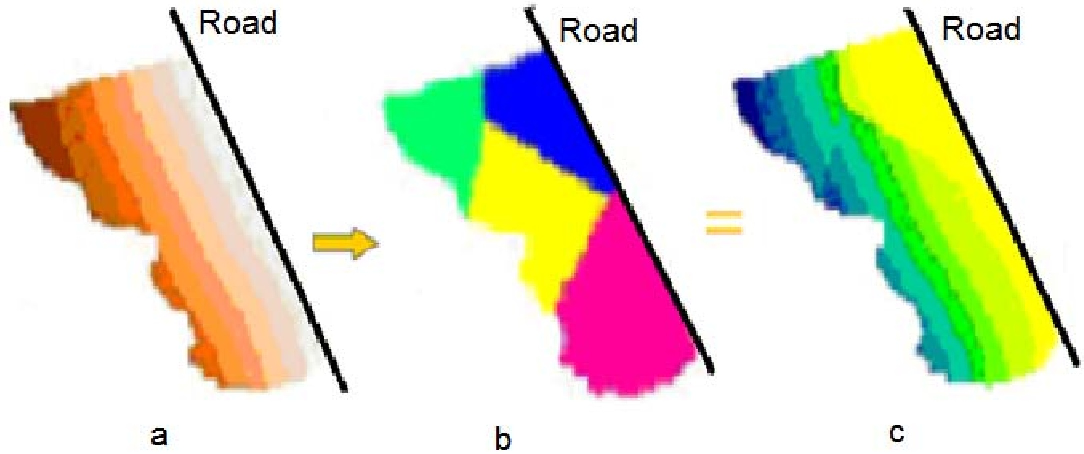

Figure 4: Illustration of the procedure to compute weighted skidding distance a) raster distance, b) weighted estimate volume per hectare with Thiessen interpolation and c) weighted skidding distance.

RESULTS

The results indicate that there were no significant differences between the three methods of estimating skidding distance a) the traditional method, b) tracking skid trails on aerial photos after harvest and c) a GIS raster procedure (*p*= 0,76) (Table 3).The mean value of skidding distance of the traditional method was 115,1 (± 67,7) m. Mean values of tracking skid trails on aerial photos and a GIS raster procedure was 108,4 ± 64,3 m and 109,1 ± 73,7 m respectively. There were not significant differences between block size, number of obstacles (*p*=0,12) and shape index (*p*=0,35) between treatments.

Table 3: Analyse of variance of three average skidding distance methods.

Source	DF	Sum of Square	Mean square	F value	*p*
Regression	2	2599	1299	0,2754	0,76
Residual	282	1330306	4717		

Analysis of variance of volume heterogeneity between sites, blocks and treatments were performed (figure 5). This analysis showed that 8.2% of the variance in volume is explained by the variability between sites, 23.9% of the variance in volume is explained by the variability between blocks and 67.7% of the variance in volumes is explained by the variation within blocks. Consequently, the volumes did not follow a uniform spatial distribution within the blocks of the studied area. Regardless, the average volumes in the three assignment methods showed no significant differences (*p*=0.68).

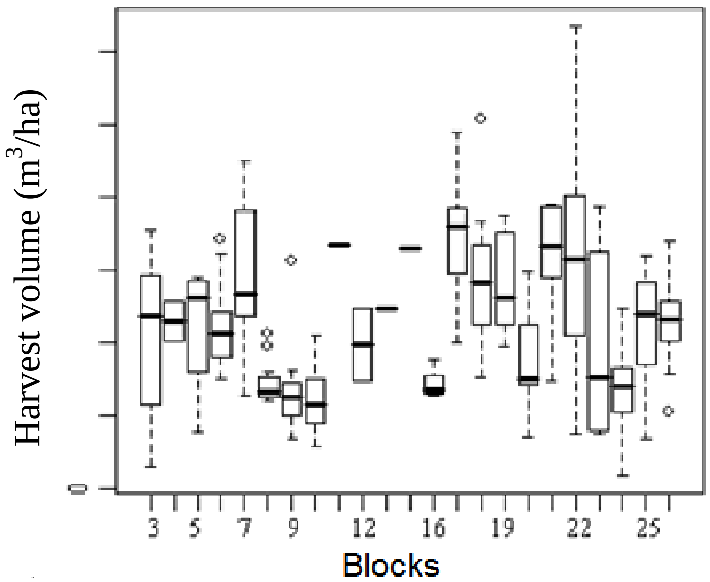

Figure 5: Boxplot of volume m^3/ha in sites: Dufay (blocks 1- 6), Fenelon (blocks 6-7), Gaudet (blocks 8-10), Maskuchi(blocks 11-24) and Puiseaux (blocks 25-26).

Our analyses of the weighted skidding distances in the studied site were performed. The volume per sample plot showed values that ranged from 0 to 302.1 m^3/ha. The average value corresponded to 86.2 ± 50.6 m^3/ha. Equation 6 that proposed the combined analysis was used with a load capacity of 1.5 m^3/turn. Two methods equation 3 and equation 6 have not showed significant differences (*p*=0, 47). The average values of the skidding distances were 109.4 ± 73.8 m and 101.6 ± 67.5 m respectively. The skidding distance values between methods did not show any significant difference, this may be explained by the low volume harvested at each position in the block. Because harvest volume was lower than the load capacity of the machine, the machine must travel at least one time at each pixel position.

Table 4: Average harvest cost ($\$/m^3$) by site, treatment and method.

Site	Treatment	processing	Skidding Equation 1	Skidding Equation 2	Skidding Equation 3	Skidding Equation 6
Dufay	CPRS	NA	3,97	3,57	3,69	NA
Dufay	CPPTM	9,25	5,01	4,89	5,12	5,12
Fenelon	CPRS	10,41	3,46	3,43	3,33	3,37
Fenelon	CPRV	6,651	4,99	4,99	5,00	4,99
Gaudet	CPRS	10,49	3,61	3,59	3,67	3,68
Gaudet	CPRV	14,84	4,30	4,36	4,17	4,18
Maskuchi	CPRS	13,43	3,69	3,62	3,53	NA
Maskuchi	CPPTM	7,83	4,62	4,35	4,33	4,32
Puiseaux	CPRS	11,54	3,36	2,96	2,98	2,91
Puiseaux	CPRV	9,64	4,23	3,90	3,89	3,90
Mean	CPRS	11,47	3,62	3,43	3,44	3,32
Mean	CPRV	10,38	4,51	4,42	4,36	4,36
Mean	CPPTM	8,54	4,82	4,62	4,72	4,72

Harvesting costs take into account skidding and processing costs. These estimated costs for the studied site showed that the cost of processing were higher than the skidding costs, processing costs were more sensitive to volume and were not affected by distance (Table 4).

In our analysis equation 1 had a higher mean value compared to the other methods. The principal reason for this difference is the manual way to get the traditional skidding distance. The accuracy depends on shape and size of blocks and preference of the analyst. Equation 3 seems the most appropriate measure to estimate the skidding distance (boreal forest) due to the effectiveness of GIS tools. In addition, it can be determined using various configurations of harvest blocks.

This study is useful when parallel skid trails are considered and it does not consider the use of individual landing zone configurations. The slope was not considered in this analysis because the studied areas consist of flat landscapes.

CONCLUSION

Our results show that the average skidding distance (equation 3) method was effective and that there was no significant difference with the equation 1 and 2. This method is an alternative to the traditional method (equation 1) inspired from Matthews 1942. Moreover, the equation 3 is simple, easy to use and available in GIS tools. We also showed that 67.7% of the variance in volume was explained by the variability within blocks. Consequently, volumes do not follow a uniform spatial distribution within the harvest blocks. To incorporate this heterogeneity within the harvest block, we proposed the Thiessen interpolation method and we noted that although statistically comparable with photo interpretation. The Thiessen method of interpolation is easily integrated with GIS tools. This method requires the identification of sample plots in each block of harvest.

Then a combination of methods using the skidding distance and volume assignments with Thiessen interpolation was proposed (equation 6). The results of this weighted skidding distance analysis showed that the skidding distance was sensitive to changes in distribution and harvest rates. Thus, the analysis of the weighted skidding distance was included in the estimated harvesting costs. The skidding costs ($/m3) in this study range, were about 10% for CPRS to 15% for CPPTM, if retention elements were considered.

Others results that were not outlined in this paper in regards to simulation models were also performed. The simulation model takes into account different distribution and volume heterogeneity within a harvest block and permits to combine different objectives of retention and obstacles. The results show that the skidding distance may vary considerably (volume, orientation, retention). The change in skidding distance and cost depend on the position and volume heterogeneity and spatial configuration of retention.

Finally, our proposal to estimate the weighted skidding distance permits the incorporation of spatial retention elements like shape, size and volume. Thus, in partial cutting, the new estimate of the skidding distance would achieve the objectives of structure and composition of a forest ecosystem, while taking into account the economic consequences of this practice in the Abitibi clay belt.

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CASE STUDY OF INTEGRATING ON-BOARD COMPUTERS IN NORTHERN ONTARIO'S FOREST SUPPLY CHAINS

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ABSTRACT

The limited application of Information Technology (IT) and OBCs in northern Ontario forest harvesting operations is an opportunity to improve the wood procurement supply chain through their implementation, development and use. OBCs will be installed in three different machine types (feller-buncher, grapple skidder, single-grip roadside processor (delimb and cross cut)) with three machines per machine type. Key Performance Indicators (KPIs) will be developed and data will be collected by multiDAT dataloggers. After initial installation, benchmark KPI data will be collected and considered as "control". Once benchmark data has been collected, it will be reported to staff and employees. After this point, all KPI data collected will be considered as "treatment". The main objective of the study is to determine if there are any significant differences between control and treatment KPI data. Secondary objectives will include testing significance between machines within a machine type, considering KPI data on different timelines (/day, /shift, /hour) and consider the machine treatment interactions.

This study will help determine the cost/benefit of data sharing and implementation of OBCs within wood procurement in Northern Ontario. If OBCs are found to have a successful impact on operations, further implementation and cultural adoption of these units would follow.

Keywords: Wood procurement, On-board Computers (OBC), Logistics, Key Performance Indicators (KPI), Supply chain

INTRODUCTION

It is a common observation by most that the forest products industry in Canada has been experiencing a downturn. This downturn is the product of many factors. Those most often cited includes the high value of the Canadian dollar, the price of energy, increases in wood costs and the reliance on low value commodity products. Other reasons include poor market and competitive positions and lack of information (IUFRO 2005; Björk and Carlsson 2006; Björk and Carlsson 2007; Skjäl *et al*. 2009). It can also be suggested that a resistance to change is one of the core causes of this downturn.

One of the available options for the improvement of the forest industry is the use of On-Board Computers (OBC) in forest supply chains. OBCs can be used as a tool to collect performance information in order to provide valuable data, identify opportunities, implement changes and monitor the effect of those changes. With a strong focus on cost reduction, the implementation of these systems would provide the next logical step in operational improvements. This is because there are many operations working without any system for collecting and understanding performance information; a key component in productivity improvement and management.

This paper summarizes a study currently taking place in Dryden, Ontario, Canada. A short literature review on OBC publications is done in order to highlight the need for this study, past OBC research and apparent challenges. This is followed by a description of the study, significance of the research, limitations of the study and conclusion.

LITERATURE REVIEW

Wood procurement supply chain

The forest industry is trending towards supply chain management (SCM). The main focus of SCM is on the order fulfilment processes and corresponding material, financial and informational flows (Stadtler 2005) with some specific attention to customer satisfaction. In order to match production with customer requirements, there is a need for improved integration among different actors in the supply chain (IUFRO 2005). This will only become more important as there is added product diversification (Davis and Kellogg 2005; IUFRO 2005) such as the harvest and transport of forest fuels (Sikanen *et al.* 2005).

Frayet *et al.* (2004) and Sikanen *et al.* (2005) suggest that the integration of an automated, open access web-based system with real-time information would provide grounds for better collaboration of all organizations. This system would need to be robust and capable of collecting, managing and storing all information (Christopher 1998; Carlsson and Rönnqvist 2005; Cordero *et al.* 2006). This would be done with a good data transmission network between the field and central database (Emeyriat and Bigot 2006). The development of such a system would require the implementation and continued use of On-Board Computers (OBC).

Types of OBCs

According to Hubbard (2000), there are two major categories for OBCs: 1) those that collect information for periodical download (trip recorders); and 2) those which provide real-time information (Electronic Vehicle Management Systems (EVMS)). He suggested that trip recorders are only used to collect vehicle data (speed, rpm, idle, etc...) for analysis at a later date, whereas EVMS provide real-time remote access to vehicle data and geographic information.

A more specific categorization was suggested by CRC for Forestry (2010) with a total of four categories: 1) vibration, 2) GPS, 3) purpose built and 4) manufacturer. Each of these categories has its own specialization, which in turn provides different opportunities. Vibration OBCs are generally all-purpose units which tend to collect very basic information with minimal user input. GPS OBCs focus on the collection of geographic information for subsequent interpretation. Purpose built OBCs are specifically built and designed as units for data collection in forestry.

Manufacturer OBCs are typically built-in systems which have been installed by the machine manufacturer for equipment monitoring and control.

Current uses of OBCs

The most common use of OBCs is loosely referred to as "monitoring". As it is a broad term, it encompasses many items; some examples are to meet environmental requirements (i.e., soil disturbance), provide opportunities for compliance reporting and improve the traceability of forest products (Taylor *et al.* 2001; Cordero *et al.* 2006).

The use of GPS tracking for monitoring forest operations has been successfully tested in many cases, including a study of forest operations traffic (Carter *et al.* 1999), soil disturbance (Taylor *et al*. 2001; Veal *et al.* 2001; MacDonald *et al.* 2002; Davis and Kellogg 2005; MacDonald and Fulton 2005) and trucking (Devlin *et al.* 2008; Devlin and McDonnell 2009). Taylor *et al.* (2001) and Husband (2010) suggest using a machine's GPS information to report on treated areas for compliance.

There is considerable interest in the use of OBCs to improve productivity. This interest is normally centred on the use of OBC information to identify and quantify opportunities for operational improvements (Davis and Kellogg 2005). However, attempting to track productivity in forestry operations can be frustrating (IUFRO 2005). This is difficult due to the heterogeneous and stochastic nature of forestry work. This, in turn, has led to a limited number of reports describing productivity gains in forestry (IUFRO 2005) (i.e., the cost benefit).

OBCs are well positioned to be employed as a tool to implement and help manage incentive systems for workers (Hubbard 2000; Husband 2010; Spinelli and Natascia 2010). Framing the implementation of OBCs as an opportunity for workers to gain additional income is an excellent way to motivate change.

One of the simplest functions of an OBC is to track machine utilization. The simplicity of this data and its collection can help drive OBC use. There is a desire to measure utilization due to its clear impact on an operation's economy and productivity (Turcotte 2003).

Another less common but growing opportunity with OBCs are their use as an activity sampling and work study tool (Davis and Kellogg 2005). The use of these units as a tool for long-term shift level studies is gaining popularity and is proving its cost efficiency. Furthermore, advances in IT are providing more opportunities and ease of use, especially the automatic transfer of data.

Current gaps

There are gaps in the implementation and operation of OBCs. The most pronounced is the lack of collecting detailed operational information and its correct interpretation (Davis and Kellogg 2005). Even though there are units which can collect more accurate mechanical information than a work study professional (e.g., JDlink) there is a lack of clarity in the data. Improvements in purpose built units, additional sensors and improved software would be needed to help rectify this issue.

Another fault within OBC systems is related to hardware. Information storage and data transfer can be challenging in the forest environment. Improved hardware is necessary in order to increase reliability. An example of lack of data storage was suggested by McDonald and Fulton (2005) and Cordero *et al.* (2006). In order to give a more accurate understanding of machine paths and activities, shorter intervals between GPS collection points would be required. This increase in data collection (i.e., a point collected every 1-2 seconds) would lead to a considerable increase in data volume, and would possibly lead to inconsistencies and problems in analysis of data

The level of detail required for data capture is another gap in OBC implementation. This will vary greatly between local applications, however guidance in collection methods and analysis are needed. The optimal collection of information would lower costs and improve analysis.

In forest harvesting operations, there often is a large inter-dependence amongst machine elements and machines. This inter-dependence inherently means that all activities performed will affect all others that follow Sundberg and Silversides (1989). When considering the use of OBCs, a complete system would be able to monitor and report on the interaction of multiple machines within a supply chain. An opportunity which has not yet been studied and published is the implementation of OBCs to monitor multiple machine interactions. The ability to monitor machine interactions would provide a slew of many new performance indicators and opportunities to improve forest operations.

An additional challenge to monitoring multiple machine interaction would be to provide comparable units between machines. Sundberg and Silversides (1988) suggest that using comparable units provides ease in computation and use of numerical values on a comparable scale: e.g., energy (GJ), power (kW), time (h) and money ($). Developing a system which can have automated monitoring of multiple machines with comparable units will be a major challenge to overcome.

Struggles in application

The greatest challenge to the implementation of these units is cultural. In the past, there has been a clear focus and an extensive amount of resources applied to the reduction of production costs (Frayet *et al.* 2004; Roscher *et al*. 2004). This has come at the cost of organizational agility (Frayet *et al.* 2004), which is the ability to efficiently adapt to change.

The implementation of OBCs is further challenged by the inherent need to use new technologies. When considering the implementation of information technology in any sector "it's not only about new technology; it is also about new ways of doing things" (IUFRO 2005). Therefore, one must understand the cultural impact of a re-organisation and re-definition of certain parts of forest operations. Due to the low hiring rate of new workers in the industry and the aging workforce, the cultural adoption of new technologies can be challenging (IUFRO 2005).

Another cultural challenge related to implementation of these units is the long history of some negative relationships between forest contractors and large forest products firms. This partially stems from the historical pressure on contractors to constantly lower costs yet still produce high quality raw materials. This has led to a sense of information hiding, mistrust and even cheating (IUFRO 2005; Stadtler 2005).

Also, a lack of interest in performance information by North American loggers was suggested as stemming from the view of timber as a commodity product, and not as a potential for individual stem optimization (McDonald and Fulton 2005) In most cases, contractors simply do not see the value of detailed performance information, and they are not interested in paying for the technology (IUFRO 2005; McDonald and Fulton 2005).

Another challenge is the initial implementation of OBCs as a system. This can be partially related to the lack of uptake of IT, however it is important to note that the initial implementation of progressive logistical improvements are not done overnight (Bowersox and Daugherty 1995). Other system implementation challenges include cost, involvement of multiple parties, the broad geographic area, remote access to these areas and the lack of communications infrastructure (Taylor *et al*. 2001; Frayet *et al.* 2004; D'Amours *et al*. 2007).

The dedicated cooperation of operators is another struggle in the application of these systems. Some of the reasoning for this challenge ties in to aforementioned cultural challenges. However, their dedicated involvement comes with considerable reward. Their extensive knowledge in the frontline operation of equipment will give the highest quality of insight on forest operations and performance.

Communication infrastructure and automation is another major struggle in the application of these units. There is a clear need for the automated production of performance information from data systems (McDonald and Fulton 2005; Thompson and Klepac 2010). Additionally, the automation of an OBC system must not add too much, if at all, to the workload of machine operators (Holzleitner *et al.* 2010). This is further reflected in Emeryiat and Bigot (2006) who suggest that if any additional data input represents too much extra work for the operators, the project will most likely be unsuccessful.

The final challenge to the implementation of these units is related to the survivability of equipment. The equipment must be able to stand up to the harsh environment of forest operations (Turcotte 2003; McDonald and Fulton 2005). Forest operations equipment are exposed to many challenging environments and elements; this includes everything from extreme cold and heat, varying humidity levels, excessive noise and vibration levels, dust, and resistance to impacts.

Lack of peer reviewed publication

Due to this technology's recent development, the amount of literature on this subject is quite limited; much like any study that looks at the effect of Information and Communications Technology (ICT) in the forest sector (IUFRO 2005). Furthermore, studies regarding ICT solutions in procurement are still often regarded as immature (IUFRO 2005). There are very few peer-reviewed journal articles which discuss or provide a case study on the implementation of OBCs in forestry. The bulk of the information found on the implementation and use of OBCs, and even GPS systems in the forest industry, is mostly restricted to non-peer-reviewed publications (Taylor *et al.* 2001).

This lack of publications is odd, since there are a large number of publications in forest planning and supply chain management which stress the importance of developing a reliable, accurate and efficient data collection system. Therefore, there is a major knowledge gap in terms of implementation and quantification of benefits.

The ability for OBCs to collect information on machine interaction is non-existent in published literature (Davis and Kellogg 2005).

MATERIALS AND METHODS

Study area

This study will be based out of Dryden, Ontario, Canada. Wood procurement operations will be taking place on the Wabigoon and Trout Lake Sustainable Forest Licenses. The specific study area within these two licenses will follow planned operations according to the current Annual Work Schedule (AWS). Following the AWS will represent actual working conditions. Due to this, operations will be taking place in a variety of stand and site conditions within the boreal forest.

OBC

OBCs will be used to collect performance information and monitor equipment. This study will use the MultiDAT electronic datalogger, which is publicly available at Castonguay Électronique in Longueuil, Québec, Canada. This unit is designed to collect information from both electronic and motion sensor input. In terms of electronic inputs, the unit is equipped with the ability to monitor four different activity channels. These channels can be connected to a signal source with a voltage between 5 and 28 V. A power connection is also required to power the unit for its operation. This requires a 12 or 24 V connection. Depending on its connection, it can also be used as an additional source of information: i.e., if it is powered by the ignition, master switch, direct from the battery, etc....

Key Performance Indicators (KPI)

KPIs will be used in order to benchmark and monitor performance. There are four main KPIs for all machines; they are referred to as “power on”, “motion sensed”, “drives engaged”, and “signal”. All machines will have identical “power on” and “motion sensed” connections. The units will be powered only when the machine ignition is activated. Therefore, “Power on” will be the KPI which tracks machine activation. The built-in motion sensor will be used as a source of information to determine when the machine is moving. This will help determine idling and delays. The “drives engaged” and “signal” inputs will be the only 2 activity channels used in all machines. “Drives engaged” refers to a connection which can measure when the track(s) or wheels are activated for machine movement. “Signal” measures a direct work function which is engaged (i.e. activating the grapple on a skidder). Specifics for these connections are listed in table 1.

Table 1: Machine types and associated connections for individual KPIs.

Machine type	Power on [power connection]	Motion sensed [motion sensor]	Drives engaged [channel 1]	Signal [channel 2]
Feller-Buncher	Ignition on [h]	Motion sensor active [h]	Drives engaged [h]	Head tip [count]
Grapple Skidder	Ignition on [h]	Motion sensor active [h]	Drives engaged [h]	Arch up [count]
Single-grip Roadside processor (delimb and cross-cut)	Ignition on [h]	Motion sensor active [h]	Drives engaged [h]	Saw [count]

Only two of the four possible channels will be used in order to reduce installation time, increase data simplicity and reliability and allow room for future development and application.

Machines

There will be three machine types: Feller-Buncher [FB], Grapple Skidder [GS] and Single-grip Roadside Processor (delimb and cross-cut) [RP]. Each machine type will have three representative machines. All of these machines are scheduled to run six days per week, 24 hours per day on three 8 hour shifts per day. MultiDATs had been previously installed in these machines, however datalogger upgrades and rewiring of connections was necessary for all units.

Data collection

Machine KPI data will be collected and stored in MultiDAT dataloggers. Each individual datalogger will be connected to a modem for wireless data transfer. Data will be transferred wirelessly to a mobile data station (located in a vehicle such as a light-duty pick-up or service truck). Subsequently, data will be transferred from the mobile station to a centralized database once it is in range of cellular service.

Benchmark data (control) will be collected in order to determine the current level of KPIs. Once an acceptable amount of benchmark data is collected, it will be reported and shared amongst staff and employees. Once data dissemination has taken place, post-treatment data (treatment) will be collected. As data is reported and interpreted by staff and employees, operational improvements can take place.

Data reporting and interpretation

Once data has been collected and transferred to the central database, it must be reported and interpreted. This will require the use of MultiDAT 5 software. This software provides an interface to create and generate reports for performance monitoring. Standardized reports will be created and used to report KPIs. Data from these reports will be used for statistical analysis. Data will be reported by machine type, individual machine and unit of time (/day, /shift, /hour). In order for data to be used within a statistical software package, data will be formatted as depicted in table 2.

Table 2: Example of raw data table for statistical analysis.

*Data sharing [1,2]	Machine type [FB, GS, RP]	Machine # [1,2,3]	**Shift #	Activation [h]	Motion [h]	Drives [h]	Productivity [count]
1	FB	1	1	6.13	4.5	0.4	320
1	FB	1	2	7.04	5.54	1.2	400
…	…	…	…	…	…	…	…

*1 indicates control. 2 indicates treatment.
**In this case, shifts are used.

Hypotheses

The main objective of this study is to determine if there are any significant differences between control KPI data and treatment KPI data within machine types. Figure 1 illustrates each individual linear model.

Per Day

Feller-Buncher		Grapple Skidder		Roadside Processor	
KPI	Linear model	KPI	Linear model	KPI	Linear model
Power on [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Power on [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Power on [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$
Vibration sensed [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Vibration sensed [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Vibration sensed [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$
Drives engaged [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Drives engaged [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Drives engaged [h]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$
Signal [count]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Signal [count]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$	Signal [count]	$Y_{ij} = \mu + M_i + T_j + MT_{ij} + \varepsilon$

Per Shift

As above except using shifts instead of days as units of time

Per Hour

As above except using hours instead of days as units of time

Figure 1: Linear models for individual KPIs within each machine type.

Where:

Y=	Response variable	= Power on, Vibration sensed, Drives engaged, Signal
μ=	Grand mean	
M=	Machine number	i = 1,2,3
T=	Treatment	j = 1,2
ε=	Random error	

SIGNIFICANCE OF RESEARCH

This research project has a number of different objectives. Its primary objective is to test if there is any significant difference between control and treatment KPI data. The result of these tests will help determine and quantify the effect of OBC use in forest operations, and thus their cost-benefit. This will provide crucial information to the industry for aid with OBC implementation and decision making. It will help determine the effective and cost/benefit of these units.

One of the secondary objectives will be to explore differences in OBC implementation amongst machine types. Since each machine type performs different tasks, the success of OBC implementation may vary. This could lead to the development of specific focus points.

Another secondary objective would be to interpret KPI data according to different units of time. The ability to consider data per day, per shift and per hour would provide additional opportunities for data analysis. This would in turn lead to recommendations as per data analysis and reporting for subsequent use.

This study would also provide the opportunity for future research through the use of other OBCs. An example of this would be to implement FPdat dataloggers in order to quantify the effect of visual OBC and GPS use on KPIs.

The final objective of this study is to help develop additional KPIs for local implementation. This would be done by working with all levels of contractor staff and identifying possibilities for significant, useful and automated KPIs.

LIMITATIONS OF RESEARCH

This study is based on the collection and statistical analysis of KPIs. KPIs are used in order to quantify and represent changes which may occur in forest operations. They should only be considered as estimates and be carefully used as guideline information to help in decision making. Subsequent development of KPIs is necessary in order to increase accuracy and relevance.

This is considered to be a large shift level study. Stand and site conditions will be monitored, however it is not in the scope of this study to monitor the effect of different site and stand conditions.

Since this is a broad level study, operator influences will not be specifically studied. Even though differences in operators have been well documented (Lindroos 2010), it is not within the scope of this study to quantify their effect on KPIs.

There may be differences in machines (year, make, model) amongst machine types. This may have an effect on the resulting control and treatment data. However, all machines within a machine type will be comparable in terms of size and power. The importance of testing with identical machines is becoming less important through time, since technological development has slowed and machine productivity and limitations are quite comparable (Lindroos 2010).

CONCLUSION

There is considerable opportunity for improvements within the forest industry in Canada, especially with IT. The aging image of the forest industry tends to lead to the idea that ICT could become a source of new opportunities and even a new image (IUFRO 2005). The implementation of IT tools within wood procurement, such as OBCs, would provide valuable information that would help improve operational efficiency. This could be driven by the need to increase efficiency and lower costs.

Furthermore, the inherent need for OBCs will only grow as new objectives and goals become a greater part of the planning and operational process (Roscher *et al.* 2004). As the achievement of these new objectives requires greater attention to system control and adaptability, there is a need for further access to more information (IUFRO 2005).

The need for a cultural change was stated by Sundberg and Silversides (1988) when they suggested that forestry now consisted of highly specialized jobs that relied heavily on proper planning and engineering. The aging approach of on-the-job training with rudimentary instructions is in the process of disappearing. They further argue that any enterprise striving for efficiency should not rely on common sense and past experience, but implement new tools and methods. Therefore, there is a clear need to collect, analyze, interpret and distribute performance information to all partners and forest contractors (Davis and Kellogg 2005).

The goal of this study is to provide valuable information for the forest industry by quantifying the effect of OBCs in order to help determine the value of their application. The willing implementation of these units will only take place once studies have clearly demonstrated the cost/benefit of these units. Further implementation and use will develop a culture of ICT and OBC use that will continually expand in order to improve operations.

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A MATHEMATICAL FORMULATION FOR THE LOCATION OF LOGGING CAMPS

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ABSTRACT

Logging activities within the forestry sector commonly take several seasons for each region. Throughout each season, the workers directly involved within the logging activities are hosted at an accommodation close to the current logging location. However, the next cities or villages are usually far away. A common solution to this problem is the construction of logging camps that contain the complete infrastructure to host the workers. Such logging camps are typically close to the logging regions, resulting in reasonable transportation times and costs. The bigger a camp, the lower the daily hosting costs per person. Hence, a small number of big camps results in lower accommodation costs than a large number of small camps. However, the fewer camps are available, the higher the transportation costs tend to be, because their geographic distribution is less flexible.

The problem studied in this paper consists in finding the optimal number, location and size of logging camps. Due to the complexity of the problem, a manual planning approach is not applicable. This work investigates the relevance and advantages of constructing additional camps for the accommodation of workers, expanding the capacities of existing camps and relocating entire camps from one region to another. A mathematical model, representing the cost structure on a very detailed level is presented. Results are given for a realistic five year harvest planning provided by FPInnovations and based on data from a Canadian logging company.

CONTEXT AND MOTIVATION

Log harvest planning in the forestry sector changed throughout the last decades. Both silviculture and harvesting became more sophisticated and include very complex and important decisions in order to get the most from the available regions and harvest cycles. Based on a complex variety of such considerations, a long-term planning is designed to determine the volume and regions for wood logging. Such decisions are commonly divided into smaller time periods.

Logging activities and road construction within a single logging region typically take several months. Workers that are directly involved in such activities need appropriate accommodation. However, due to the vast extension of the country, logging regions in Canada are widely distributed and often located far from the next city or village. Accommodating the workers in the closest village or city is therefore rarely an attractive option, as the commuting time and transportation costs are too high. Furthermore, an additional salary is commonly paid when the transportation times exceed a certain threshold.

A common solution to this problem is the construction of logging camps in which the workers are accommodated. These logging camps are typically located close to the logging regions so that the transportation costs for the workers are reasonable. Workers are usually transported by pick-ups, using a given road network. The transportation costs are composed of the transportation and working time of the workers as well as the vehicle costs, i.e. renting and gas costs. Allocating each working crew to a camp, the accommodation costs are given by a cost per day per worker. In order to host all workers, the construction of new accommodations may be necessary. The bigger a camp, the smaller the daily cost per person. Hence, a small number of big camps results in smaller accommodation costs than a large number of small camps. However, the fewer camps are available, the higher the transportation costs tend to be, because their location is less flexible. The construction of a new camp may pay off in the long-term as the traveling costs to the logging regions may be much lower.

This work investigates the possibility of constructing additional camps for the accommodation of workers, considering the harvest planning for the next five years. The problem consists in finding the number of camps that have to be constructed, their size in terms of capacities and their location such that the total costs given by the accommodation and transportation costs are minimal. The interesting question is whether such an investment of camp constructions pays off, considering the operational planning of the next five years. It is assumed that all information about workers, logging regions and distances are given at the beginning of the planning and not subject to uncertainty. The problem was inspired by the needs of a Canadian logging company and will now be explained in detail.

PROBLEM DESCRIPTION

Based on an existing overall planning, the logging company provides a harvest plan for the next five years. Each year is divided into two seasons: winter and summer, each with a certain number of available working days. The winter season begins mid-November and ends mid-March, whereas the summer season typically begins mid-June and ends mid-November. Depending on the geographical location, some regions will be logged more in winter whereas other regions will be logged more in the summer season. Each region is defined by its estimated log volume (measured in m^3) that is subject to harvesting (it may be part of the strategic decision that not the entire region will be harvested) within each season and the length of the road (measured in km) that has to be constructed in that region in order to transport the log.

Working Crews, Demands and Hosting Capacities

There are two types of working crews: logging and road construction. Crews of the same type contain the same number of members. The members of a crew always stay together during work and are hosted at the same accommodation. For each logging region and season, a logging and road construction demand is given. Based on given productivity rates for the working crews one can compute the average number of crews necessary to cover the demand at each region for each season.

Example: A crew type works 100 days within a given season and cuts 120 m^3 per day, i.e. 12,000 m^3 within the season. A certain region holds a total demand of 30,000 m^3 within the season. Throughout 50 days, three logging crews will be working (i.e. 3 x 50 x 120m^3 = 18,000m^3). The other 50 days, two cutting crews will be working (i.e. 2 x 50 x 120m^3 = 12,000m^3). This results in an average allocation of 30,000/12,000 = 2.5 logging crews within that season.

We can assume that the crews of each working type are flexible in respect to the days they work within each season. That is, if a crew works only a few days within a season, one may assume that it does not matter at which days the crew works within the season. In our case, it does not matter in which of the 100 days we use three crews and in which we use only two crews. In practice, a working crew may work a number of days in one region and then in another region in the same season. In order to determine the minimum capacity necessary to host all working crews allocated to a certain accommodation, consider the following *example*:

We decide to host the workers from two regions at the same camp. One region has an average demand of 1.4 logging crews and 0.7 road construction crew. The other region has an average demand of 1.2 logging crews and 0.5 road construction crews. So we have a total demand of 1.4 + 1.2 = 2.6 logging crews and 0.7 + 0.5 = 1.2 road construction crews. Hence, for 60% of the time during the season there will be $\lceil 2.6 \rceil = 3$ logging crews and 40% of the time there will be $\lfloor 2.6 \rfloor = 2$ logging crews. In the same way, 20% of the season there will be $\lceil 1.2 \rceil = 2$ road construction crews and the other 80% of the season there will be only $\lfloor 1.2 \rfloor = 1$ road construction crew. Assuming that a logging crew has six workers and a road construction crew has three workers, we will need an accommodation for $\lceil 2.6 \rceil$ x 6 + $\lceil 1.2 \rceil$ x 3 = 18 + 6 = 24 workers. To determine the minimum capacity of an accommodation, we can hence sum up all the average numbers of crews allocated to this accommodation and round up the sum to the next highest integer (for each crew type). Figure 1 illustrates such a scenario for two regions, each with an average demand of 1.5 crews. Transportation costs for commuting from the accommodations to the logging regions are given for each crew type for each pair of regions.

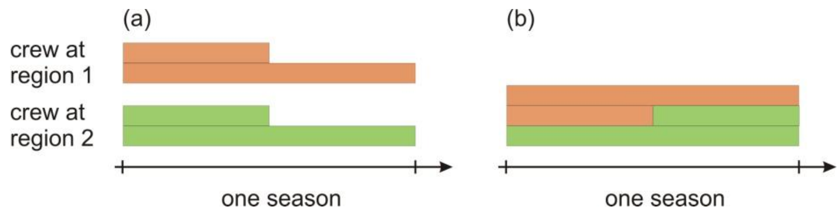

Figure 1: Example of logging demands hosted at the same accommodation

Camps and Trailers

Certain accommodations for the workers already exist. These accommodations may be either hosting options within villages or cities (apartments, hotels, etc.) in reasonable distance to the logging regions, or camps that are usually located within the forest close to the logging regions. Accommodations vary in their capacity and their hosting costs. Camps include a number of trailers. A trailer contains the entire infrastructure to host a certain number of workers. In practice, trailers of different capacities are available. However, we may assume that the trailer with a capacity for twelve persons is the most common. Hence, we assume that all trailers have the same capacity. In addition to the trailers that host workers, a camp contains a number of additional trailers that provide complementary, but necessary infrastructure, such as a kitchen. The number of additional trailers directly depends on the number of hosting trailers, i.e., the total hosting capacity of the camp. In the following, we will measure the capacity of a camp by the number of hosting trailers. Hence, the construction costs for a number of hosting trailers already include the costs for the necessary number of additional trailers.

Trailers can be either open or closed. Only open trailers are available for use. Trailers that are not in use have to be closed, involving closing costs. Once a trailer is closed, it cannot be used in subsequent seasons until it is reopened, involving reopening costs. Such closing of an open trailer or reopening of a closed trailer can only be performed once a year before the summer season. Reopening and closing costs commonly involve economies of scale in the number of hosting trailers involved. This is not only due to the involved additional trailers, but also because they share common resources. The use of hosting trailers in order to accommodate workers involves two types of daily costs: fixed costs for each open trailer (including the cost for the trailer itself, its equipment, the cook, etc.) and variable costs (food, etc.) for each worker. The fixed costs are paid for each open trailer (in $) per day. Costs for closed trailers are so small that they do not have to be considered. Variable costs are paid for each worker hosted at the camp. If a trailer is open, its fixed costs have to be paid throughout the entire season, independent of its use. All costs may follow the principle of economies of scale, i.e. the bigger the quantity, the lower the price-per-worker/trailer. New camps can only be constructed at certain places from a given set of potential locations. It is very common that several logging regions are served by workers from the same accommodation. In the same way, one logging region may be served by workers from different accommodations.

Capacity Expansion and Camp Relocation

At certain points during the planning it may be interesting to increase the capacity of existing camps. Such capacity expansion is performed by adding new trailers. It is assumed that the cost of adding *k* trailers is the same as the construction of a new camp with *k* trailers. In contrast, permanently closing a part of a camp or even the entire camp is not considered. Hence, it is not possible to partially close (permanently) a camp and relocate the other part. Camps can only be relocated as a whole.

Logging regions are not equally logged in each year. That is, a camp may be close to logging regions with demands in certain years, but far away from logging regions that will be harvested afterwards. Instead of constructing a new camp, which involves high costs, camps can be relocated from one location to another. Relocations of camps can only be performed once a year: right after the winter season. The costs for relocating a camp from one location to another depend on the distance and the size of the camp (i.e. the number of trailers it includes). As the costs caused by the actual distance of the relocation are very low, one may not consider them within the model. All trailers have to be closed before relocating a camp. After the relocation, all trailers that are supposed to be in use have to be reopened again. In theory, camps from two distinct locations can also be joined to further reduce the costs per unit. Trailers from the same camp could also be relocated to distinct locations. In practice, none of these features are observed. Hence, we assume that camps can only be relocated as a whole and that we cannot join two different camps at the same location.

Objective

Given that all logging and road construction demands must be covered, we need to ensure that sufficient accommodations are available to host the workers. We want to minimize the total cost which is composed of two parts:

All costs involved in providing the necessary accommodations: Camp construction, maintenance for open trailers, closing and reopening of trailers, hosting costs for workers and camp relocation.

The transportation costs between the accommodations and the logging regions. This includes the costs for using the vehicles and an additional salary for long transportation times.

A solution to the problem consists of the following information, given for each of the seasons within each of the years of the planning horizon:

Where to construct a new camp of which size.

For each accommodation: how many logging and road construction workers are hosted and at which region they work.

For each camp: the number of trailers that will be closed and reopened.

For each relocation: the origin, destination and size of the relocated camp.

Throughout this work, we will refer this problem to the *Camp Size and Location Problem (CSLP)*.

MATHEMATICAL FORMULATION

Related Literature

The given problem belongs to the family of Facility Location Problems. It can be formulated as an extension of the Capacitated Facility Location Problem (CFLP). The CFLP aims at finding the optimal locations to construct an unknown number of facilities with capacity constraints. All customer demands have to be covered and the total costs, usually composed by costs for facility construction, production and transportation, are minimized. Within the last decades, many variations of the CFLP have been addressed in literature, containing different features such as multi-periods, multi-commodities, multiple capacity levels, multi-stages, capacity reduction, expansion and relocation. Many of such features can be found within the proposed CSLP.

Instead of reviewing all of these works, we list those that had the most influence on our model and note that the CSLP contains two features which, to the best of our knowledge, have not been addressed in the Facility Location literature:

Temporary deactivation of facility parts. Related features that have been considered in the literature include capacity reduction, capacity relocation or complete facility shutdown. Partial and temporary deactivation (which is commonly less expensive than a complete shutdown) has not yet been considered.

Capacity constraints with round-up to the next highest integer. The sum of all average numbers of working crews allocated to the same accommodation must be rounded up to the next highest integer (separately for each crew type) to determine the necessary capacity of the accommodation. Crew types can be seen as different commodities.

Closely related works include those of Shulman (1991), Peeters and Antunes (2001), Melo et al. (2005) and Troncoso and Garrido (2005).

Mathematical Model

The mathematical model is an extension of the CFLP. A network flow structure is added in order to manage the dynamic aspects of the problem throughout the planning horizon: closing and reopening of trailers, construction of new trailers and relocation of trailers. The network structure is illustrated in Figure 2. For each time period, two nodes for open trailers and two nodes for closed trailers are used. Between these nodes, closing and reopening of trailers is possible. In addition, relocation is possible from one region to another.

All accommodations are modeled as camps. Existing accommodations such as hotels can be modeled as special cases of the camps with adapted costs and without the possibility of closing, adding or relocating trailers. It follows the input data for the mathematical model:

I Set of locations where new camps can be constructed.

J Set of logging regions which possess logging and/or road construction demands.

K Set of possible sizes for potential camps. $K = \{0,1,2,\dots,kMax\}$.

P Set of different working crew types: logging and road construction.

T Set of time periods, representing the different seasons within the different years.

d_{jpt} Average # of crews necessary to cover demand of type *p* at region *j* within period *t*.

u_k Total hosting capacity (in # of workers) of a camp with *k* open trailers.

c_{in}^{C} Construction cost of a camp with *n* trailers at location *i*.

c_k^{TO} Cost to reopen *k* existing trailers that were closed.

c_k^{TC} Cost to close *k* existing trailers that were open.

c_{kt}^{F} Operating fixed cost for entire season *t* for a camp with *k* open trailers.

c_{ijkpt}^{V} Variable costs (hosting and transportation) for the entire time period *t* for a crew of type

$c_{i_1 i_2 k}^{R}$ Relocation costs for a camp with *k* (closed) trailers from i_1 to i_2.

nW_p # of workers within a working crew of type *p*.

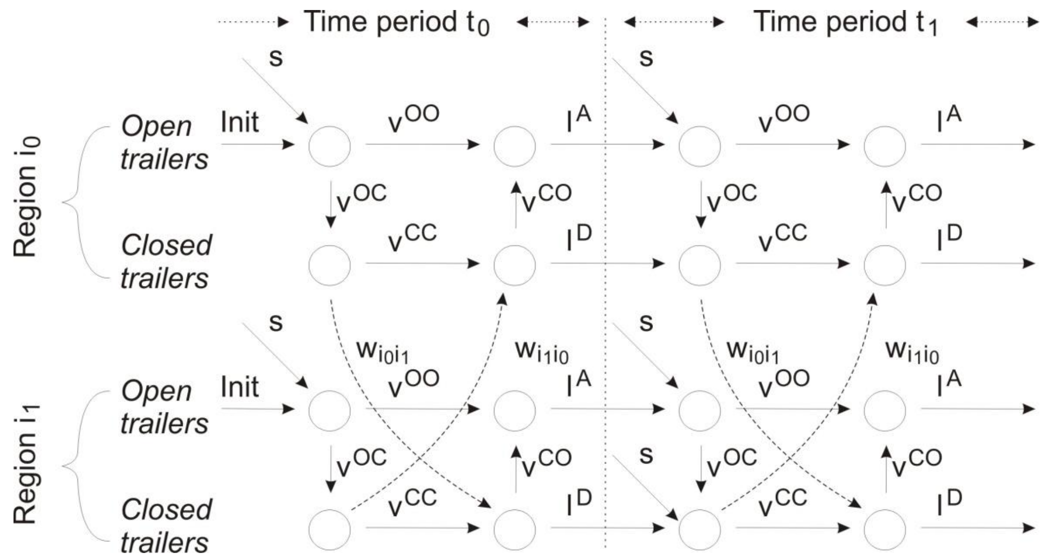

Figure 2: Network model to manage open and closed trailers at each location

The model uses the following decision variables:

$x_{ijkpt} \in \mathbb{R}^+$ Total # of working crews of type *p* allocated from a camp at location *i* with *k*

$y_{ikt} \in \{0,1\}$ *1*, if the camp at location *i* has *k* open trailers at time period *t*. *0*, otherwise.

$z_{ikpt} \in \mathbb{Z}$ Maximum # of crews of type *p* working at the same time throughout period *t*

$s_{int} \in \{0,1\}$ *1*, if *n* trailers are constructed at location *i* right before period *t*. *0*, otherwise.

$l_{it}^{A} \in \mathbb{R}^+$ # of open trailers at location *i* during time period *t*.

$l_{it}^{D} \in \mathbb{R}^+$ # of closed trailers at location *i* during time period *t*.

$v_{it}^{OO} \in \mathbb{R}^+$ # of open trailers that will not be relocated to from location *i* before period *t*.

$v_{it}^{CC} \in \mathbb{R}^+$ # of closed trailers that will not be relocated from location *i* before period *t*.

$v_{it}^{OC} \in \mathbb{R}^+$ # of open trailers at location *i* that are closed right before period *t*.

$v_{it}^{CO} \in \mathbb{R}^+$ # of closed trailers at location *i* that are reopened right before period *t*.

$v_{ikt}^{BCO} \in \{0,1\}$ *1*, if *k* closed trailers are reopened location *i* right before period *t*. *0*, otherwise.
$v_{ikt}^{BOC} \in \{0,1\}$ *1*, if *k* open trailers are closed at location *i* right before period *t*. *0*, otherwise.
$w_{i_1 i_2 t} \in \mathbb{R}^+$ # of trailers that are relocated from location i_1 to i_2 right before period *t*.
$w_{i_1 i_2 kt}^{B} \in \{0,1\}$ *1*, if *k* trailers are relocated from location i_1 to i_2 right before time period *t*.

The mathematical model is given by:

$$min \quad \sum_{i\in I}\sum_{n\in K}\sum_{t\in T} c_{in}^{C}\, s_{int} + \sum_{i\in I}\sum_{k\in K}\sum_{t\in T} c_{kt}^{F}\, y_{ikt} + \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{p\in P}\sum_{t\in T} c_{ijkpt}^{V}\, x_{ijkpt} \tag{1}$$

$$+ \quad \sum_{i\in I}\sum_{k\in K}\sum_{t\in T} c_{k}^{TC}\, v_{ikt}^{BOC} + \sum_{i\in I}\sum_{k\in K}\sum_{t\in T} c_{k}^{TO}\, v_{ikt}^{BCO} + \sum_{i_1\in I}\sum_{i_2\in I}\sum_{k\in K}\sum_{t\in T} c_{i_1 i_2 k}^{R}\, w_{i_1 i_2 kt}^{B}$$

$$s.t. \quad \sum_{i\in I}\sum_{k\in K} x_{jikpt} = d_{jpt}\,;\forall j \in J\,;\forall p \in P\,;\forall t \in T \tag{2}$$

$$\sum_{j\in J} x_{jikpt} \le z_{ikpt}\,;\forall i \in I\,;\forall k \in K\,;\forall p \in P\,;\forall t \in T \tag{3}$$

$$\sum_{p\in P} nW_p \;\; z_{ikpt} \le \; u_k\, y_{ikt};\forall i \in I\,;\forall k \in K\,;\forall t \in T \tag{4}$$

$$\sum_{k\in K} y_{ikt} \le \; 1;\forall i \in I\,;\forall t \in T \tag{5}$$

$$x_{ijkpt} \le d_{jpt} y_{ikt}\,;\forall i \in I\,;\forall j \in J\,;\forall k \in K\,;\forall p \in P\,;\forall t \in T \tag{6}$$

$$Init_{it} + l_{i(t-1)}^{A} + \sum_{n\in K} n\, s_{int} = v_{it}^{OO} + v_{it}^{OC}\,;\forall i \in I\,;\forall t \in T \tag{7}$$

$$v_{it}^{OO} + v_{it}^{CO} = l_{it}^{A}\,;\forall i \in I\,;\forall t \in T \tag{8}$$

$$l_{i(t-1)}^{D} + v_{it}^{OC} = v_{it}^{CC} + \sum_{i_2\in I} w_{i i_2 t} \;\;;\forall i \in I\,;\forall t \in T \tag{9}$$

$$v_{it}^{CC} + \sum_{i_1\in I} w_{i_1 i t} = v_{it}^{CO} + l_{it}^{D}\,;\forall i \in I\,;\forall t \in T \tag{10}$$

$$l_{it}^{A} + l_{it}^{D} \; \le kMax\,;\forall i \in I\,;\forall t \in T \tag{11}$$

$$\sum_{k\in K} k\; y_{ikt} = l_{it}^{A}\,;\forall i \in I\,;\forall t \in T \tag{12}$$

$$v_{it}^{CC} + v_{it}^{OO} \le kMax - kMax \sum_{i_2\in I}\sum_{k\in K} w_{i i_2 kt}^{B} \;\;;\forall i \in I\,;\forall t \in T \tag{13}$$

$$\sum_{i_2 \in I} \sum_{k \in K} w^B_{i i_2 k t} \leq 1 \; ; \forall i \in I \; ; \forall t \in T \tag{14}$$

$$\sum_{i_1 \in I} \sum_{k \in K} w^B_{i_1 i k t} \leq 1 \; ; \forall i \in I \; ; \forall t \in T \tag{15}$$

$$\sum_{k \in K} k \, v^{BCO}_{ikt} = v^{CO}_{it} \; ; \forall i \in I \; ; \forall t \in T \tag{16}$$

$$\sum_{k \in K} k \, v^{BOC}_{ikt} = v^{OC}_{it} \; ; \forall i \in I \; ; \forall t \in T \tag{17}$$

$$\sum_{k \in K} k \, w^B_{i_1 i_2 k t} = w_{i_1 i_2 t} \; ; \forall i_1 \in I \; ; \forall i_2 \in I \backslash \{i_1\} \; ; \forall t \in T \tag{18}$$

$$\begin{aligned}
&x_{ijkpt} \in \mathbb{R}^+ ; \forall i \in I \; ; \forall j \in J \; ; \forall k \in K \; ; \forall p \in P \; ; \forall t \in T \\
&y_{ikt} \in \{0,1\} \; ; v^{BCO}_{ikt}, v^{BOC}_{ikt} \in \{0,1\} \; ; \; \forall i \in I \; ; \forall k \in K \; ; \forall t \in T \\
&z_{ikpt} \in \mathbb{Z}^+ \; ; \forall i \in I \; ; \forall k \in K \; ; \forall p \in P \; ; \forall t \in T \\
&s_{int} \in \{0,1\} \; ; \forall i \in I \; ; \forall n \in K \; ; \forall t \in T \\
&l^A_{it}, l^D_{it}, v^{OO}_{it}, v^{CC}_{it}, v^{OC}_{it}, v^{CO}_{it} \in \mathbb{R}^+ \; ; \forall i \in I \; ; \forall t \in T \\
&w_{i_1 i_2 t} \in \mathbb{R}^+ \; ; \forall i_1 \in I \; ; \forall i_2 \in I \backslash \{i_1\} \; ; \forall t \in T \\
&w^B_{i_1 i_2 k t} \in \mathbb{R}^+ \; ; \forall i_1 \in I \; ; \forall i_2 \in I \backslash \{i_1\} \; ; \; \forall k \in K ; \; \forall t \in T
\end{aligned} \tag{19}$$

The objective function *(1)* minimizes the total costs. *(2-4)* represent the demand and integer capacity constraints. *(5)* guarantees that we construct at most one camp at each location. *(6)* is a valid inequality to strengthen the bound given by the linear programming relaxation of the problem. Flow conservation within the network structure is represented by *(7-10)*. In *(7)*, $Init_{it}$ represents the number of trailers that initially exist at location *i* at period *t*. *(11)* limits the maximum camp size. *(12)* sets the value of the *y* variables. *(13-14)* ensure that camps are only relocated as a whole. *(15)* says that two different camps cannot be joined to one camp at the same location. *(16-18)* link the binary decisions in order to enable modular capacity depended costs within the objective function. *(19)* determine the variable domains. Note that the arc variables for the network flow will have integer values due to the unimodularity property of the network flow matrix. In addition to these constraints we use additional valid inequalities in order to reduce the large integrality gap caused by the presence of the integer capacity constraints.

EXPERIMENTS

A real-world instance has been provided by FPInnovations. The instance includes 29 locations, each with logging and road construction demands. One location contains an existing hotel and four locations possess existing camps (# of trailers: 2, 3, 4 and 4). All locations allow for the construction of new camps. Demands are given for summer and winter seasons throughout five years. Table 1 shows the cost allocation within the optimal solution for two scenarios: in the first scenario, we only use the existing accommodations and do not permit the relocation of camps. Within the second scenario, we allow the relocation of camps and the construction of new ones. The optimal solution for the second scenario suggests the relocation of a camp with four trailers to another location after the second year. The savings in transportation due to this camp relocation outweigh the relocation costs. This permits a saving of 8.6% of the total costs (representing over 600,000$) when compared with the first scenario.

Both scenarios described above have been solved by CPLEX12.0 within less than 30 minutes, using a single CPU of a 2GHZ Sony Vaio notebook with 4GB of memory. Based on the real-world instance, further instances have been generated with different properties and different sizes: (10/20), (10/50), (29/29), (50/50) and (50/100). The first number indicates the number of possible camp locations. The second number indicates the number of logging regions. The experiments showed that most of the instances with 50 possible camp locations could not be solved within a given time of 60 minutes.

Table 1: Cost distribution for scenarios without and with camp construction and relocation

Cost ($)	Scenario 1	Scenario 2
Construction	0	0
Hosting	1,879,905	1,476,083
Transportation	2,261,810	1,353,561
Camp Maintenance	3,235,633	3,593,936
Camp Relocation	0	317,096
Total	7,377,348	6,740,676

CONCLUSIONS

We presented a mixed-integer model that investigates optimal locations for logging camps in the forestry sector. The model considers the partial and temporary closing of camps, i.e. trailers, camp expansion during the planning horizon and the relocation of camp from one location to another. Economies of scale are modeled in almost all types of cost. Experiments showed that the model grows large as we increase the number of possible camp locations and clients. Within short computing times, the MIP solver CPLEX cannot solve many of the instances generated. This suggests the investigation of more sophisticated solution techniques, such as mathematical decomposition.

ACKNOWLEDGEMENTS

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DEMAND DRIVEN-HARVEST SCHEDULING

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ABSTRACT

The forest sector is at the heart of the debate on globalization and sustainable development. For many countries like Canada, Sweden and Chile, the objective is to maintain a flourishing sector without damaging the environment. It is important to be competitive and to operate effectively, from harvesting to manufacturing products, in a context where costs increase rapidly. Our project belongs to the area of value chain optimization. We develop tactical/operational models to plan the annual harvesting activities in order to meet demands at the mills, while integrating transportation and inventory management. Our mixed-integer programming (MIP) models address the assignment of harvest teams to forest areas over a one-year period, as well as the quantities transported from the forest to the mills and the levels of inventory to maintain in the forest and at the mills. We present and compare different MIP formulations, which are solved through a rolling-horizon method that decomposes the models by time periods, each of the resulting submodel being solved by heuristic branch-and-bound. We present computational results on actual large-scale instances derived from the context of the Eastern Canadian forest.

Keywords: Forestry, harvest planning, value chain, mixed integer programming, rolling horizon approach

PROBLEM DESCRIPTION

First, we describe the supply chain between the forest and the mills. The supply chain is defined by five activities: building roads, harvesting, storing wood in dedicated areas, transporting wood from the forest to the mills, storing wood at the mills.

Context

Forest field. The forest field is divided into two levels. The smallest unit is an area. And the largest one is called a sector which is constituted by a set of adjacent areas. Every harvest area includes volumes of different wood assortments, and has specific access restrictions. At the beginning of the annual planning, the set of areas available for harvesting for the year is already known. For an annual planning, moving between two areas in the same sector, witch takes about 10 minutes, is considered instantaneous, as every period of the planning horizon corresponds to 140 hours (2 weeks of work). Moves between sectors require other expensive engines, and need 3 hours in the worst case to be done. Hence, we have to limit the moves between sectors especially when the sectors are very far away from each other.

Road network. Road network is already designed. Each harvesting area needs a single access road. The only decisions we have to take about roads are when they are built, and by which team of workers. Roads are regarded as "harvesting areas " which must be built prior to the harvesting areas served by these roads.

Harvesting teams. Harvesting is done by teams of workers divided into two types: short woods and long woods. For each team type *h* and for each area *b* a capacity of production p_{bh} is defined. This quantity is the volume a team of type *h* can harvest on area *b* during a period of two weeks. We note that, on average, an area can be harvested in three periods of two weeks. But, there are small areas that can be harvested in less than two weeks. Thus, a team can harvest more than one area in a single period. Also some areas can only be harvested by one type of team.

Transportation. Transportation is associated to flow volumes between the forest and the mills. Our project does not include fleet scheduling, or routing problem, or triage in yards. There is no explicit destination in our problem, as each product has a single destination corresponding to the mill requiring this product.

The problem in details

For each activity, there is a set of constraints, which we summarize next.

Harvesting. Team assignment has to verify different access conditions as a area can be harvested only if the road which serves has been built. Some areas are not available for every period during the year, since various restrictions due to hunting, thaw, environmental protection, must be respected. For every forest unit (area and sector), an upper bound has been introduced to prevent situations where too many teams are in the same place. Only one team can work in an area at each period, and five teams can be in the same sector at each period. As soon as a team is assigned to an area, it has to work continuously on it, until there is no more wood to harvest in this area. Obviously, an area can only be harvested once. Following the assignment of a team to an area there are two cases:

- the size (volumes of all assortments) in the area on which the team is working is superior to the team's capacity of production per period, this team cannot work anywhere else during this period;
- if this team's capacity of production is superior to the size of the area, this team can work an another area.

We illustrate these situations with a small example. An area *b* has 100 m^3; the capacity of production of a team during a period of two weeks is 200 m^3this team has to work only half a period to entirely harvest area *b* But if the capacity of production of that team was 50 m^3per period of two weeks, as soon as this team is working in this area, it cannot be in another area during this same period. The team stays in this area until there is no more wood to harvest in this area.

Periods of two weeks allow situations where the harvesting of an area can start anytime during a period of two weeks. The ending time harvest period is the first period when there is no more wood to harvest in the area. T_{bq} is the number of periods of two weeks needed by team q to entirely harvest the area b. If q starts harvesting b at period t the ending time period can be $t + T_{bq} - 1$ or $t + T_{bq}$ according to the proportion of the starting period t the team q is working. If the harvesting of area b starts soon enough, the ending time period is $t + T_{bq} - 1$, it is $t + T_{bq}$ otherwise. A short example to illustrate these possibilities follows. If the harvest of b starts soon enough in the period t (Case A), the ending time period is $t + T_{bq} - 1$ Otherwise it is $t + T_{bq}$. Colored zone in the figure indicates working proportion time period (Figure 1).

Consider a team q starts harvesting b at period t. Real harvesting time is 2,8. $T_{bq} = \lceil 2{,}8 \rceil$

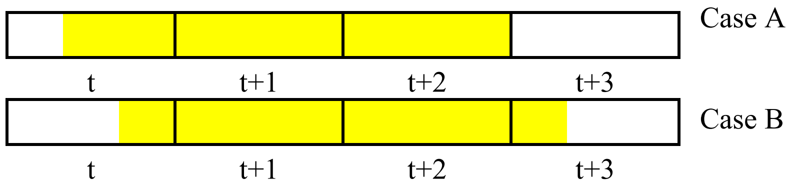

Figure 1: Determination of the ending harvest period of an area

We direct the harvesting effort according to the demands d_{kt} of the mills. By $\tilde{d}_{kt}$ we evaluate the effort that has to be done at each period to satisfy demands at the current period and at the next ones. This way, we manage harvesting effort according to variation of future demands. If the harvesting effort $\tilde{d}_{kt}$ is not reached, lacking volumes are penalized. This penalty is called « delayed production cost » .

Storage in forest areas. Harvested volumes are left on the roadside. Some are for transportation, others stay in storage areas. However, we want to prevent situations when too many products stay on the roadside, losing value.

Transportation. All transported volumes are first delivered to the main mill, before their final destination. An upper bound ξ_b on the total volume transported from each area b to the main mill is introduced, to represent the distance between the area and the main mill. More an area is far away from the main mill, smaller is the upper bound associated to this area. In the contrary, the closer the area, larger is the upper bound.

Storage at mills. A part of the transported volumes are required to satisfy mills demands, remaining volumes stay in storage. For some product k, at each period, a minimum volume m_{kt} is required for safety purposes, but this minimum is not rigid. If needed, this quantity can be used for consumption. If demands cannot be met, we introduce slack variables l_{kt} which are very penalized in the objective function. These quantities will be called « orders » .

Goal Project. For on year planning horizon, divided into 26 periods of two weeks each, we look for a near-optimal harvest scheduling, which minimizes harvesting, inventory, transportation cost.

LITERATURE REVIEW

We do not intend to present an exhaustive review of operations research (OR) applications in forestry, but give a short indication where our projects stands.

Value chain optimization and forestry

Shapiro et *al.* [9] maintain that the optimization of the value chain of a company starts with a quantitative analysis to optimize the bonds between activities, and continues with the development of tools for sharing informations and making decisions. He also justifies why mathematical programming is appropriate for integrating planning problems, emphasizing that most integrating planning processes can be formulated as linear or mixed integer problems. The article by D'Amours et *al.* [1] proposes an overall picture of OR uses for forest value chain planning. In the introduction, the challenges for OR researchers in forestry are listed, one of the major and undoubtedly more complex one being the integration of a broad forest chain activities where the different and many agents have divergent ends (« many to many processes »). The importance to integrating decisions from distinct planning levels is also emphasized as well as in [10].

Optimization in forestry

For a field as wide as the forestry, it is interesting to know the contexts and the degrees of OR involvement. Many forest activities like green up, road network design, cutting strategies, harvesting, vehicle routing etc, have been the subject of scientific research. Within this section, a quick overview of different OR tools used in forest activities is given. Rönnqvist [8] describes the wood flow within a forest planning and a variety of problems associated to planning at different hierarchical level. Each element of the supply chain has a detailed description. The author presents examples of real problems for each planning level, the type of model used and the common solution method.

Epstein et *al.* [2] present several decision-making systems established in the Chilean forest sector. They insist on their effectiveness, the savings obtained and the practical use of the systems. We mention the tool OPTICORT, which is a decision-making system for short-term harvesting (three months), because it is similar to our context. In OPTICORT, planning is based on harvesting and transportation decisions. We specify that the management of the inventories is not included. OPTICORT is based on a linear model which is solved by column generation.

Harvest planning

Karlsonn et *al.* [4] deal with a problem of annual harvest planning from the point of view of Swedish companies. These article objectives are very close to our project. If the objectives are alike, mathematical formulations are clearly distinct. A major difference is the harvesting duration of an area. Every area needs one period to be harvested. In our models, the harvesting duration varies not only with the surface of the areas, but also with the team productivity and can last more than two periods. Moreover, even if the forest territory partition is also on two levels (areas, sectors), the problem applies only to areas from the same sector. We note however the largest number of areas (approximately 400 compared to 184 in our case) in their project. They propose heuristics whose behavior is similar to Branch-and-Bound, where branching rules are based on harvesting. Lacroix's master thesis [5] provides important details about the context of our problem, and presents operational issues considering environmental protection of the forest in Québec.

Very short-term planning

Finally, Karlsonn et *al.* [3] provide a project of operational planning which binds this level of planning to tactical planning. For one period of 3 to 6 weeks, the objective is to choose among a whole of calendars, one for each team. A cost is associated to each calendar, including harvest, displacements between sectors, transport and the inventories. To the usual constraints of transport and inventory, those are added representing the maintenance and the management of the roads. Mitchell [7] gives a very detailed definition of operational harvest scheduling, applied in New-Zealand and Australia companies.

SOLUTION APPROACH

We developped two MIP models. The first one (M1) considers every harvest team. This formulation is intuitive but we notice symmetry between team of same type. Because most of parameters are defined according to type, not team individually, we could develop another model (M2) to break this symmetry. But we had to introduce other constraints to ensure the consistence between a type team scheduling and the team scheduling. Most of the constraints in M1 remain with a light modification, but some as to be reformulated. *A priori* it is not obvious which model will be more efficient. Even if there is less symmetry in M2, the additional constraints could slow down the solution time.

We solve the models on an actual instance, provided by FPInnovations. All computations are performed on a Dual Core AMD Opteron(tm)Processor 285. We chose to use some options of CPLEX12 for large scale MIP, as priorities branching [11] and polishing. After the first or second feasible solution, the « polishing » of this solution starts. Polishing is MIP heuristic provided by CPLEX.

Even with these user options in CPLEX, a direct solution of our models for 26 periods cannot be done in a reasonable time and consume a lot of memory.

Rolling horizon approach

Only short horizons can be solved easily. The rolling horizons approach is about solving a short horizon, save variables associated to some periods. After that, a longer horizon is solved, there are fixed variables. The process goes on until there is fixed variables for 26 periods. For our tests, we use 3 periods horizons, and fix variables associated to the first period.

nFix = number of fixed periods at each horizon
nLg = number of periods at each horizon
nBTours = number of horizons
iT =0
s(iT) = best solution from iTth horizon
Step 1 : Problem for NT = nLg + iT.nFix
Fix variables for periods $t <$ iT.nFix
Solve problem for NT = nLg + nFix.iT periods with variables associated to iT.nFix first periods are fixed
Save the best solution found in s(iT)
iT←iT+1
Step 2 : Si iT< nBTours
Go to Step 1
Step 3 : Fin de la résolution
Output is harvest planning for nBTours.nFix+nLg.

Figure 2: Rolling horizons resolution pseudocode

We define 2 stopping criteria:

- time limit of 3 hours by horizon
- acceptable gap of 5\%

Rolling horizon on the whole model or on some constraints. Our models can be divided in two subproblems. The first one is a MIP problem. All harvesting constraints are in it. Remained constraints constitute un LP subproblem. Rolling horizons can only be done on the MIP subproblem. After 26 iterations, the LP problem associated to transport and storage management can be solved for 26 periods. It is not obvious what constitutes the best strategy to gain a good annual schedule. *A priori* solving an annual transport-storage problem, can give a better management of volumes, and reduce orders. So, for each model, we will compare witch strategy is more efficient: rolling horizons on the whole model, or only on harvesting constraints then a 26 LP subproblem to solve. Every strategy is summarised:

M1_C1: Rolling horizon on whole model 1, Polishing after finding 1 feasible solution
M1_R1: Rolling horizon on harvesting constraints from model 1, transport-storage LP suproblem resolution for 26 periods, Polishing after finding 1 feasible solution
M1_C2: Rolling horizon on whole model 1, Polishing after finding 2 feasible solutions
M1_R2: Rolling horizon on harvesting constraints from model 1, transport-storage LP suproblem resolution for 26 periods, Polishing after finding 2 feasible solutions
M2_C1: Rolling horizon on whole model 2, Polishing after finding 1 feasible solution
M2_R1: Rolling horizon on harvesting constraints from model 2, transport-storage LP suproblem resolution for 26 periods, Polishing after finding 1 feasible solution
M2_C2: Rolling horizon on whole model 2, Polishing after finding 2 feasible solutions
M2_R2: Rolling horizon on harvesting constraints from model 2, transport-storage LP suproblem resolution for 26 periods, Polishing after finding 2 feasible solutions

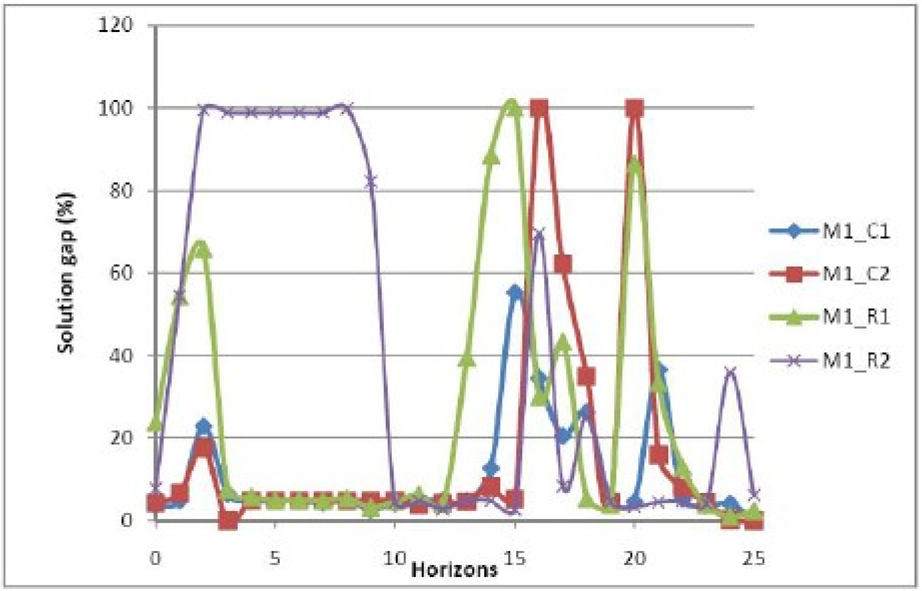

Figure 3: M1 Solutions gap per horizon

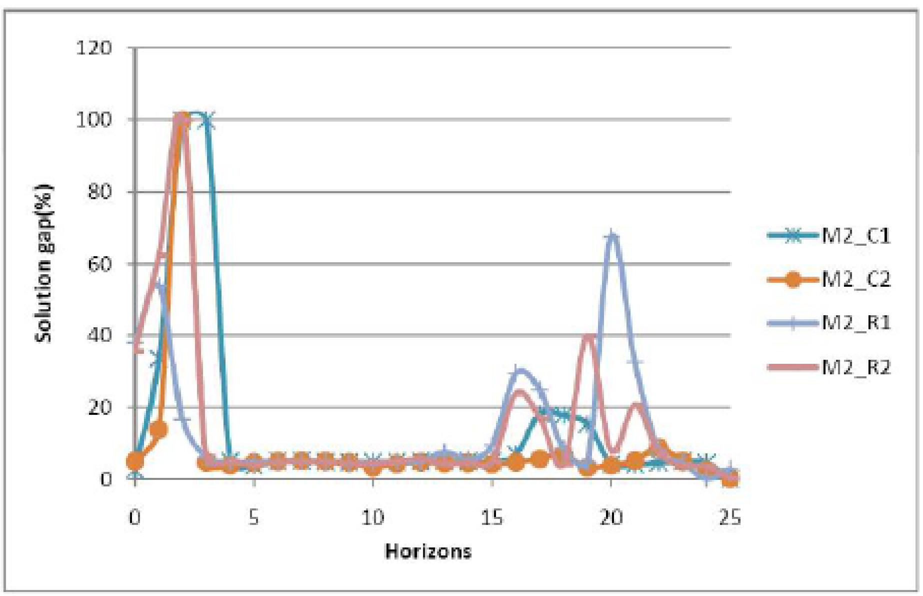

Figure 4: M2 Solution gap per horizon

CONCLUSIONS

Thus we developed two models in order to establish an annual harvest calendar for each team with an aim of satisfying the mills requests. This calendar can be obtained in less than one day. By analyzing our results, the best choice between the two models is not absolute. However M2 solutions are at the top of the strategies. Even if such a calendar is viable in reality, various points should be improved in particular the reduction of the ordered quantities, and thus to approach optimality. However it seems that the use of compact methods has reached its limits. It would be also interesting to know the influence of a greater number of areas on the resolution. The orders relate to only one product. If the forest field is larger, other choices of areas can be made in order to increase the harvest of this product which misses, without inflating the inventory of the other products less required. Thus, the annual planning could be different, maybe faster, even if the number of generated constraints explodes. Indeed larger is the number of stands, larger will be the offer by product. Thus the availabilities and the conditions of access could play in favour of a faster resolution. For next work, we will exploit a column generation approach. It will then be a question of determining schedules for each team over the year. These schedules will have to be feasible and will have to observe the various harvesting conditions. Harvesting production will always be guided by the demands, without forgetting the minimization of the costs of harvest, of inventories and transport.

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EFFECT OF TIMBER HARVESTING GUIDELINES ON FELLING AND SKIDDING PRODUCTIVITY IN NORTHERN MINNESOTA

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ABSTRACT

We empirically evaluated how varying degrees of applying Minnesota's Timber Harvesting and Forest Management guidelines, along with operator and tract-specific variables, impact felling and skidding productivity of mixed aspen/hardwood/conifer stands in northern Minnesota. Felling and skidding productivity data from five mechanized logging businesses were collected on 52 clearcut harvest blocks from August 2006 to March 2007 using time-motion and geospatial sensors. Post-harvest data were collected using high resolution aerial photography and detailed on-site inventories. Regression analyses determined that felling productivity was influenced by guideline, tract and operator variables. Skidding productivity was influenced by both guideline and tract variables. Variables that were statistically significant in explaining felling productivity include the logger's use of a pre-harvest site map and/or pre-harvest meeting with the forester, harvesting in winter, merchantable timber volume per unit area, and the operator. Variables that were statistically significant in explaining skidding productivity were the area of landings and skid trails as a percent of the harvest area, ratio of the harvest block perimeter to the block area, slope, and merchantable timber volume per unit area. The findings suggest implementing the guidelines we studied has minimal effect on felling productivity, though several adversely affect skidding productivity. By considering how to lay out the harvest block to facilitate skidding efficiency, a feller operator may be able to reduce the impact of some guidelines on skidding productivity.

Keywords: Economics, timber harvesting productivity, GPS recorders, regression

INTRODUCTION

Substantial investment has been made in the development and application of scientifically-based best management practices (i.e., guidelines) that are intended to protect and enhance the ecological, environmental, and aesthetic attributes of forest resources (Kilgore and Blinn 2004). These guidelines have been developed in response to growing public concern about the need to mitigate the perceived and actual negative environmental impacts associated with various timber harvesting and other forest management activities. Minnesota's voluntary site-level forest management guidelines (MFRC 2005) were designed to mitigate the perceived and actual negative environmental impacts on clean water, cultural resources, riparian areas, soil productivity, wetlands, wildlife habitat, and visual quality.

While society across the accrues many benefits from correctly applied timber harvesting and forest management guidelines (e.g., clean water, enhanced wildlife habitat, protected habitat of endangered and threatened species), their application has been reported to reduce landowner income through a reduction in stumpage prices, decreased harvestable timber volume, and increased time required to set up timber sales (Kilgore and Blinn 2003, Cubbage 2004, Blinn and Kilgore 2005). The degree to which these modified harvesting practices impose additional financial cost to the logging business depends on site and stand characteristics, harvesting equipment, and operator proficiency (Kilgore and Blinn 2003).

While past research provides considerable information on how site and stand variables (i.e., harvest volume per acre, tree specie composition and size) and a limited number of guideline variables impact felling and skidding productivity, no studies have examined how a more comprehensive suite of timber harvesting guidelines, along with tract and operator variables, impacts felling and skidding productivity. Therefore, we empirically evaluated how the application of Minnesota's Timber Harvesting and Forest Management guidelines (hereafter "guidelines"), operator and tract-specific variables impacted felling and skidding productivity of mixed aspen/hardwood/conifer stands in northern Minnesota.

METHODS

The study's observational units were 52 spatially separated harvest blocks in northern MN, centered around Grand Rapids, MN, that were harvested from August 2006 to March 2007. The average harvest block area was 6.5 ha and ranged from 0.4 to 25.9 ha. Total area of the 52 harvest blocks was 336 ha.

Quaking aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.) represented more than 60% of the growing timber by volume in the 52 harvest blocks. Clearcutting was the silvicultural prescription for all harvest blocks. Total harvest volume per block varied from 72.3 to 4,001.4 m^3 with a mean harvest volume of 1,216.5 m^3. Harvest volume varied from 77.0 to 318.9 m^3/ha among harvest blocks.

Harvesting was accomplished by five independent logging businesses who volunteered to participate in the study. Although selection of these logging businesses was not random, selection criteria for all firms included in the study included the following: they had at least 10 years of logging experience, used similar felling (on tracks with a self-leveling cab) and skidding (rubber-tire grapple skidder) equipment, full-tree skidded trees to a landing for delimbing, harvested only stumpage sales purchased on the open market, operated one feller-buncher (hereafter feller) and two grapple skidders per harvest block, and conducted no manual felling. Using one feller and two grapple skidders on the harvest block is a typical equipment configuration in Minnesota, common to nearly 90% of the logging businesses in northern part of the state (Powers 2004).

Each feller was equipped with a Yellow Activity Monitoring System (YAMS) electronic vibration recorder (Kinetic Electronic Designs CC 2009). YAMS recorders, which store machine vibrations electronically and are capable of recording up to 114 hours of machine activity between data downloads, have been used in other studies to evaluate harvesting equipment productivity (e.g., Thompson 2001). YAMS data was downloaded on a weekly basis during the operator's scheduled break periods to avoid interfering with the normal operations of the study participants. Felling productivity per harvest block was estimated as a function of merchantable timber volume harvested and total felling productive time per harvest block.

Skidding productivity and infrastructure design were assessed using global positioning system (GPS) recorders, consisting of one Garmin GPS 18-5Hz receiver and DGPS-XM4-ALT datalogger per skidder (Garmin 2009, Keskull 2009). The recorders were installed on all skidders to continuously record point locations (i.e., coordinates) for each machine at a four-second interval. GPS recorder data was downloaded on a weekly basis. Skidding productivity per harvest block was then estimated as a function of merchantable timber volume harvested and total skidding productive time per harvest block.

Non-stereo, natural color aerial photography at a 1:5,000 scale was taken for each harvest block during leaf-off condition shortly after the harvest operation was completed. The photography was rectified, converted to a TIFF file, imported into ArcGIS 9.2, and then used to identify the size, boundaries, and shape of harvest blocks, the location of tree clumps and individual scattered leave trees, infrastructure elements and water bodies, and to help direct the on-site, post-harvest data collection. GPS data was imported into ArcGIS to determine the location of productive and non-productive skidder operations across the harvest block, skidding distances, the location, number, and size of landings, and the location, length, density, and use intensity of skid trails.

Harvest and residual timber volume per hectare and slash distribution were assessed via a post-harvest field survey during spring and summer 2007 using a 5% systematic random transect sampling approach following the technique described by Sparks et al. (2002). Parallel transects 1.5 meters wide were established at 30 meter intervals across each harvest block. Within each transect the species of all standing residual trees and stumps were identified, with tree diameters at breast height estimated to the nearest centimeter from stump dimensions using regression coefficients developed by Raile (1978). Merchantable timber volumes were subsequently estimated using net volume equations for the aspen-birch cover type for northeastern Minnesota (Raile 1980). On the eight harvest blocks for which mill-scaled timber volume data was available, the estimated harvest volume for each harvest block was compared to the total merchantable volume actually removed from the harvest block using consumer scaling tickets. A paired, two sample t-test for differences in the means of the field-based and scaled harvest volume estimates ($P(t_7 > 2.3646) = 0.0604$) indicates a mildly significant difference.

We fit two sets of models, one to describe the productivity of the felling operation (FELPROD) and the other to describe the productivity of the skidding operation (SKIDPROD). Dependent variables were felling productivity and skidding productivity, where each was measured in cubic meters harvested per productive hour of machine operation. For skidding, the total productivity for both skidders working in the harvest block was assessed. Table 1 contains a description of the independent variables by category, along with expected effects of each on felling and skidding productivity.

Table 1: Independent variables tested for effect on felling (FELPROD) and/or skidding (SKPROD) productivity.

Variable	Description	Data source(s)	Expected effect	
			Felling	Skidding
Guideline variables				
ADMIN	Active administration by forester or landowner occurred during the timber sale (1 if active administration occurred, 0 otherwise)	Logger and forester	-	-
CLUMPS	Percentage of area within the block covered by clumps	1, 2, 3	-	-
SCATTREE	Number of scattered leave trees per hectare	1, 2, 3	-	-
STRLDENS	Percentage of area within the block covered by skid trails with at least 3 passes	1, 2, 4	NA	+
LANDDENS	Landings per hectare within a block	1, 2, 3, 4	NA	+
MAP	Harvest block map or pre-harvest on-site meeting	Logger and forester	+	+
PERIAREA	Ratio of harvest block perimeter to block area (M/ha)	1, 2, 4	-	-
WINTER	Block harvested during the winter (1 if a winter harvest occurred, 0 otherwise)	4, 5	+	+
SLASH	Slash was redistributed back across the harvest block (1 if redistribution occurred, 0 otherwise)	3	NA	-
Tract variables				
VOLUME	M^3/ha of timber harvested	3	+	+
FLAT	Slope was relatively flat with 0 - 5% slope (1 if slope was relatively flat, 0 otherwise)	3	-	-
OWNER	Landowner was public (1 if public, 0 otherwise)	Logger and forester	-	-
Logger variables				
SYSTEM1[6]	Logger 1 harvested the block (1 if Logger 1, 0 otherwise)	Logger	Unknown	Unknown

[1]Post-harvest aerial photography
[2]ArcGIS
[3]Post-harvest, on-site inspection
[4]GPS data
[5]YAMS data
[6]Similar System$_i$ variables were created for logging businesses $i = 2, 3, 4$, and 5

The general models estimated were of the following form:

$$y^F = f^F(G_i, T_i, O_i, \varepsilon_i^F), \quad (1)$$
$$y^S = f^S(G_i, T_i, O_i, \varepsilon_i^S) \quad (2)$$

where y^k is productivity in cubic meters of timber per hour; $k = F, S$ refer to felling and skidding productivity respectively; G_i , T_i , and O_i , represent guideline, tract and operator variables, respectively, for harvest block *i;* and the ε_i^k are random error terms. In a series of regression models based upon (1) and (2), we investigated the effect of guideline-related activities on felling and skidding productivity (our primary research question) as well as the potential for other variables to affect the relationship of interest.

It is possible to estimate models (1) and (2) as separate ordinary least squares (OLS) models. Given that all of the variables, dependent and explanatory alike, come from the same harvest blocks, it is likely that OLS methods will produce inefficient estimates. This is because the error terms ε^F and ε^S are likely to be correlated. Any unmeasured or unmeasurable variation in harvest blocks might exert its influence in both models. One method of addressing this possibility that is commonly used in econometrics is an approach that Zellner (1962) called seemingly unrelated regression (SUR) equations. The SUR approach exploits variation in both models by estimating them simultaneously, using generalized least squares techniques. A Breusch-Pagan χ^2 test (Breusch and Pagan 1979) can then be performed to determine whether the SUR estimates are preferred statistically to the independent OLS estimates.

RESULTS AND DISCUSSION

Average felling and skidding productivity were 41 and 37 cubic meters per hour, respectively (Table 2). The other continuous variables show considerable variability. For example, the percent of area devoted to clumps ranged from 1 to 30 and the percent of area devoted to skid trails ranged from 4 to 35 percent. The volume of harvested material per hectare varied from 77 to 318 cubic meters.

Table 2: Descriptive statistics for study variables across the 52 harvest blocks.

Variable	Units	Min	Mean	Max	St Dev
FELPROD	m^3/hr	23.200	40.990	59.080	9.951
SKPROD	m^3/hr	24.650	37.440	51.110	7.974
ADMIN	"Yes" = 1	0.000	0.885	1.000	0.323
CLUMPS	% of area	1.000	7.249	30.130	5.807
SCATTREE	Trees/ha	1.480	27.970	67.950	17.136
STRLDENS	% of area	4.000	14.220	35.200	5.941
LANDDENS	Landings/ha	0.060	0.260	0.800	0.185
MAP	“Yes” = 1	0.000	0.365	1.000	0.486
PERIAREA	m/m^2	0.010	0.029	0.070	0.013
WINTER	"Yes" = 1	0.000	0.731	1.000	0.448
SLASH	"Yes" = 1	0.000	0.865	1.000	0.345
VOLUME	m^3/ha	77.030	195.470	318.850	67.043
FLAT	"Yes" = 1	0.000	0.635	1.000	0.486
OWNER	"Yes" = 1	0.000	0.615	1.000	0.491
SYSTEM1	"Yes" = 1	0.000	0.327	1.000	0.474
SYSTEM2	"Yes" = 1	0.000	0.308	1.000	0.466
SYSTEM3	"Yes" = 1	0.000	0.115	1.000	0.;323
SYSTEM4	"Yes" = 1	0.000	0.135	1.000	0.345
SYSTEM5	"Yes" = 1	0.000	0.115	1.000	0.323

We estimated the felling and skidding model pairs using Zellner’s (1962) SUR methodology (Tables 3 and 4). Models 1-a (in Table 3) and 1-b (in Table 4) were estimated simultaneously as a pair of seemingly unrelated regressions (guideline only models), as were Models 2-a and 2-b (guideline and tract variable models), 3-a and 3-b (guideline, tract, and operator variable models), and 4-a and 4-b (preferred felling and skidding models). A Breusch-Pagan χ^2 test was performed to determine whether the SUR specification was preferred statistically to the corresponding two independent OLS equations. The last two rows of Tables 3 and 4 contain the values of the Breusch-Pagan χ^2 statistic and associated *p*-value for each test. Since the felling and skidding models were run simultaneously in the SUR analysis, the χ^2 statistics and associated *p*-values are the same for each corresponding pair of models (e.g., Models 1-a and 1-b). In all cases, we reject the null hypothesis that the individual OLS specification is correct, in favor of the SUR alternative.

Table 3: Results for seemingly unrelated regression log-log felling models. Dependent variable is log(FELPROD); s.e. in parentheses. Significance codes: * $p < .1$; ** $p < .05$; and *** $p < .01$.[1]

Explanatory variable	Model 1-a	Model 2-a	Model 3-a	Preferred Model 4-a
Intercept	3.47671***	1.94341***	1.49135***	1.57916***
	(0.3740)	(0.5419)	(0.5148)	(0.5108)
ADMIN	-0.02051	-0.02437	0.09483	0.08104
	(0.1000)	(0.0948)	(0.1003)	(0.0985)
log(CLUMPS)	-0.07185*	-0.03735	-0.04729	-0.05001
	(0.0372)	(0.0304)	(0.0304)	(0.0300)
MAP	0.20066***	0.19003***	0.18421***	0.18003***
	(0.0641)	(0.0603)	(0.0558)	(0.0555)
log(PERIAREA)	-0.01867	-0.04761	-0.01567	-0.02453
	(0.0688)	(0.0561)	(0.0552)	(0.0546)
log (SCATTREE)	0.01104	0.02454	0.03314	0.03123
	(0.0479)	(0.0399)	(0.0371)	(0.0370)
WINTER	0.23016***	0.06405	0.19475**	0.17274**
	(0.0727)	(0.0758)	(0.0773)	(0.0762)
log(VOLUME)		0.24694***	0.31827***	0.30195***
		(0.0703)	(0.0710)	(0.0700)
FLAT		0.20292***	0.10464	0.11633
		(0.0660)	(0.0715)	(0.0703)
OWNER		0.06709	0.03790	0.03900
		(0.0664)	(0.0704)	(.06908)
SYSTEM1			0.11877	0.10240
			(0.0893)	(0.0837)
SYSTEM2			-0.03933	-0.01428
			(0.0884)	(0.0829)
SYSTEM3			0.29589**	0.26677**
			(0.1245)	(0.1166)
SYSTEM4			0.05688	0.04188
			(0.1434)	(0.1348)
Mult R^2	0.3672	0.6276	0.7345	0.7306
Adj R^2	0.2828	0.5478	0.6437	0.6384
Breusch-Pagan χ^2	17.8147***	12.2894***	8.1404***	8.7200***
p-value	0.0000	0.0005	0.0043	0.0031

[1]Because the felling and skidding models were run simultaneously in the analysis, the χ^2 statistics and associated *p*-values are the same in Tables 3 and 4 for each corresponding pair of models (e.g., Models 1-a and 1-b).

The last column of Tables 3 and 4 presents our preferred joint model. The felling productivity model (Model 4-a) includes all three sets of variables: guideline, tract, and operator. The skidding productivity model (Model 4-b) includes guideline and tract variables.

Table 4: Results for seemingly unrelated regression log-log skidding models. Dependent variable is log(SKPROD); s.e. in parentheses. Significance codes: * $p < .1$; ** $P < .05$; and *** $p < .01$.[1]

Explanatory variable	Model 1-b	Model 2-b	Model 3-b	Preferred Model 4-b
Intercept	2.92225***	2.25278***	2.01499***	2.22722***
	(0.3343)	(0.4730)	(0.5003)	(0.4735)
ADMIN	0.03317	0.09553	0.13797	0.09714
	(0.0785)	(0.0841)	(0.1016)	(0.0844)
log(CLUMPS)	0.01141	0.03117	0.03718	0.03059
	(0.0278)	(0.0264)	(0.0294)	(0.0265)
log(STRLDENS)	0.16753***	0.13875**	0.12998*	0.15215**
	(0.0497)	(0.0536)	(0.0581)	(0.0567)
log(LANDDENS)	0.11068**	0.10333**	0.10317**	0.11279**
	(0.0434)	(0.0455)	(0.0487)	(0.0481)
MAP	0.02007	-0.02128	-0.00911	-0.02465
	(0.0501)	(0.0543)	(0.0562)	(0.0545)
log(PERIAREA)	-0.10145	-0.10111	-0.07635	-0.10963*
	(0.0614)	(0.0614)	(0.0698)	(0.0627)
log(SCATTREE)	-0.00463	0.00157	-0.00906	0.00222
	(0.0356)	(0.0349)	(0.0362)	(0.0349)
WINTER	0.11028*	0.04402	0.11104	0.04009
	(0.0567)	(0.0660)	(0.0777)	(0.0660)
SLASH	-0.08407	-0.07076	-0.07009	-0.09206
	(0.0588)	(0.0601)	(0.0702)	(0.0640)
log (VOLUME)		0.12332*	0.17154**	0.12239*
		(0.0661)	(0.0734)	(0.0667)
FLAT		0.11588*	0.07548	0.10879*
		(0.0610)	(0.0750)	(0.0614)
OWNER		-0.06206	-0.06524	-0.05541
		(0.0592)	(0.0697)	(0.0595)
SYSTEM1			0.03713	
			(0.0897)	
SYSTEM2			-0.07786	
			(0.0885)	
SYSTEM3			0.08977	
			(0.1237)	
SYSTEM4			0.02643	
			(0.1471)	
Mult R^2	0.5360	0.6347	0.6809	0.6380
Adj R^2	0.4365	0.5223	0.5351	0.5267
Breusch-Pagan χ^2	17.8147***	12.2894***	8.1404***	8.7200***
p-value	0.0000	0.0005	0.0043	0.0031

[1]Because the felling and skidding models were run simultaneously in the SUR analysis, the χ^2 statistics and associated *p*-values are the same in Tables 6 and 7 for each corresponding pair of models (e.g., Models 7-a and 7-b).

Our analysis shows that felling productivity was significantly influenced by only two of the guideline-related variables: the use of a site map during harvest or pre-harvest meeting with the forester or landowner and winter harvesting. The use of both guidelines increased felling productivity. It is surprising the four guideline variables hypothesized to negatively impact felling productivity (ADMIN, CLUMPS, PERIAREA, and SCATTREE) have no statistically significant effect as their degree of implementation changes. This is contrary to our expectation but one can argue that, especially for the last three of these variables, the result seems reasonable. A feller covers virtually all operable areas of the harvest block. Consequently, its productivity is not likely to be slowed by the presence of clumps and leave trees. Similarly, this might explain why an oddly shaped stand does not inhibit felling productivity. The fact that the ADMIN variable is insignificant suggests that any problems identified during sale administration required little additional felling productive time. With a focus on sustaining Minnesota's forest resources, the guidelines are generally thought to increase the cost of timber harvesting. At least with respect to these four guideline variables, this does not appear to be the case using productivity as a proxy measure of cost.

Felling productivity increased as the volume per hectare harvested increased, as expected. Felling productivity is not influenced by topography. This is not as we expected, but the slopes were generally flat enough that it took little time to level the cab whenever slope changed, minimizing the impact on travel and felling speed. The result that the OWNER variable is insignificant is unexpected.

There is little variation in felling productivity among the five logging companies, even though all of our statistical tests indicate that these variables belong in the model. Only the SYSTEM3 coefficient is significantly different from zero. We conclude that this operator is more productive than the other four.

Skidding productivity is significantly influenced by three of the guideline-related variables: STRLDENS, LANDDENS, and PERIAREA. Skidding productivity responded positively to increases in the density of infrastructure associated with skid trails and landings. This is as expected, as more infrastructure enhances skidder speed and/or shortens the roundtrip travel distance to acquire and bring timber to the landing As the PERIAREA variable increases, meaning that the tract is more irregularly shaped, all else equal, skidding productivity declines. This is also as expected, for it means that the skidder must make longer turns. In these three cases, our results show that guideline implementation inhibited skidding productivity within a harvest block.

Six of the guideline-related variables included in the skidding model do not appear to influence skidding productivity. We expected that active administration of the harvest (ADMIN) would inhibit skidding productivity as the operator might reroute skidding patterns to avoid problem spots (e.g., wet areas, leave tree clumps). This is not apparently the case within our harvest blocks. We conjecture that the operators were able to harvest the stand efficiently given the operating restrictions on the timber sale imposed by the supervising forester and/or landowner. The feller operator may have also been creating bunches for skidding such that productivity impacts from the variables we measured are minimized. The presence of leave tree clumps (CLUMPS) is also insignificant in determining skidding productivity. Again, we conjecture that the size and location of clumps throughout a harvest block, decisions that the feller operator likely made, mitigated marginal reductions in travel speed and/or increases in distance that a skidder would otherwise had to travel on each round trip through the harvest block.

Somewhat surprising is the lack of influence of the MAP variable on skidding productivity. Skidding patterns, and hence productivity, are substantially influenced by the decisions made by the feller operator. It could be that regardless of whether a site map was used or pre-harvest meeting occurred, the feller operator's harvest patterns would be similar for a given stand – it just takes more time for the operator to figure out what these patterns should be. Thus, loss in productivity due to not having a site map or pre-harvest meeting is largely borne by the feller operator.

We conjecture the finding that SCATTREE is not important in determining skidding productivity is related to the same reasons that CLUMPS is also not an important factor. A skilled feller operator can leave trees in a pattern that does not inhibit the skidder's efficient travel through the tract. We were surprised that the WINTER and SLASH variables do not appear to influence skidding productivity. This may warrant further investigation.

Skidding productivity is weakly influenced by the VOLUME and FLAT variables (*p*-values of 0.074 and 0.084, respectively). In the former case, the skidder can deliver a given quantity of timber to a landing more quickly if the volume of merchantable timber per hectare is greater. In the latter case we note that, unlike the feller, which covers less ground, the skidder can also travel more quickly over flat terrain than steep. Skidding productivity does not appear to be significantly lower on publicly owned tracts.

CONCLUSIONS

Our study demonstrated that felling and skidding productivity are influenced by both common and unique factors. One factor influencing both felling and skidding productivity is the volume harvested per unit area. None of the guideline variables we evaluated were found to be significant in both operations. Influential factors unique to felling productivity include the season of operation, use of a planning map or conducting a pre-harvest meeting with the forester or landowner, and the operator. Those factors uniquely influencing skidding productivity are skid trail and landing density, the shape of the harvest block, and terrain. A feller operator can reduce the impact of guidelines on skidding through the layout of bunches for skidding.

While some of the guideline variables we thought would influence felling and skidding productivity were significant, many were not. The harvest operations we evaluated were carried out 8-9 years after the guidelines were published, and all operators had at least three years of harvesting experience. These factors combined lead us to believe that logging companies have figured out how to apply the guidelines in a manner that minimizes their adverse effects on logging productivity. Had we monitored harvest blocks shortly after the guidelines were first published, we suspect additional guidelines would have been found to adversely impact felling and skidding productivity.

Although not verifiable with our dataset, it may be that applying the guidelines can actually increase the overall productivity of logging firms. For example, the guideline recommending that the logging crew develop a harvest block map or meet with the supervising forester or landowner before beginning the harvest operation can avoid costly mistakes that decrease productivity. Similarly, the results indicating that backhauling slash from the landing across the block did not significantly decrease skidding productivity seems counter-intuitive. Yet, one could reasonably argue that logging operations have been more carefully planned as a result of the guidelines so that slash distribution does not impose marginally significant additional skidding travel time or distance. If the guidelines do increase logging efficiency, this would be consistent with Michael Porter's hypothesis that environmental regulations can prompt innovation that improves firm competitiveness (Porter 1991). Given the surprising lack of influence many of the guideline variables had on harvesting productivity, there is some evidence that this innovation is indeed occurring. Further investigation along these lines is warranted.

In spite of the surprising lack of influence guidelines appear to have on felling productivity, our data suggests that applying some of the guidelines decreased skidding productivity. In particular, following the recommendations to minimize the density of infrastructure and allow harvest blocks to follow natural stand boundaries (instead of being rectangular) all decreased skidding productivity for the logging firms we studied. It appears that, despite the loggers' best efforts to diminish the impact of these guidelines on productivity, their ability to mitigate those impacts has limitations.

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CUT TO LENGTH WOOD PROCUREMENT PLANNIG MODEL: EXACT AND HYBRID APPROACHES

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ABSTRACT

In this paper we develop three MIP models for a real life wood procurement-planning problem based on cut-to-length (CTL) bucking system, for the eastern Canadian context of operations, where bucking patterns are not determined by on-board computers. This important problem in forest management is difficult to solve since it integrates the stem bucking problem and the multi-commodity supply planning problem. This problem is characterized by the simultaneous minimization of a combined non-linear harvesting cost (i.e., the harvesting cost increases non linearly with the number of harvested products) and an aggregated transportation cost, and the maximization of the value of bucking products (i.e., profit maximization). Each model was used to evaluate a different harvesting scenario: the first scenario aims to apply one bucking pattern to each stand; the second scenario aims to apply a bucking pattern for each sector (i.e., a group of stands predefined by the forest company); and the final one aims to apply a bucking pattern for each species. The aim of these scenarios is to explore the effects of the harvesting system structure on the harvesting cost. These scenarios allow investigating the gains and losses that could arise from the use of bucking sectors aggregation. The first two problems were solved using a linearized mathematical model. For the third model, we develop a hybrid approach based on Large Neighbourhood Search, Tabu Search heuristic and Linear Programming. In tests and comparisons between the developed methods, we found that bucking sectors aggregation significantly reduces the forest company's profit.

Keywords: Cut to length bucking, wood procurement planning, Mixed Integer Programming, Large Neighbourhood Search, Tabu Search.

INTRODUCTION

(Uusitalo 2005) defines the wood procurement as a set of distinct activities (technical, commercial and logistical) included in the process of supplying wood manufacturing mills with wood raw material, and considering at the same time the most crucial characteristics of the conversion process and the final product. Adopting the definition of (Chauhan and al. 2009), we also present the cut-to-length wood procurement planning problem addressed in this paper as a combination of two classic problems: The multi-commodity supply planning problem with multiple supply sources and demand destinations and the cut-to-length based bucking problem. The cut-to-length based bucking is the operation of cutting tree stems into smaller logs so that they can be used in further industrial process (Arce 2002, kevinin 2007, Pickens and al. 1997), using the cut-to-length harvesting procedure. This later is a harvesting system where tree stems are cross-cut directly at the stump. It is widely used for wood procurement by forest companies since it facilitates the handling of logs, but it is a divergent process since only one raw material produces (tree stem) a variety of sub-products (logs) at forest stands. A better fit between the mills' demand and the supply of logs (the output of the bucking operation) has been shown as an even more important target in wood procurement development than the harvesting and transportation cost minimization objective. In fact, a good bucking has a direct impact on the end products, so on the profit of wood mills. It is also an irreversible process, as it is impossible to correct a poor bucking output at any subsequent step of a forest supply chain (kevinin 2007, Usenius 1986). In addition, when the tree bucking and the wood supply planning are considered separately, some of the supply plans may be infeasible due to the heterogeneity of the forest (Chauhan and al. 2009). In this paper we try to better coordinate the activities involved in the wood procurement planning. The content of this article is organized as follows. We begin with an overview of the literature. Then, we describe the problem and we present its formulation for each scenario. We end with some concluding remarks and we propose some research perspectives.

LITERATURE REVIEW

Based on the decomposition of the wood procurement planning problem into the bucking optimization problem and the multi-commodity supply planning problem, presented by (Chauhan and al. 2009), we will present briefly these problems in this section.

Bucking optimization problems

Stem and stand level bucking optimization problems
(Laroze 1999) classified the bucking optimization problems into three categories: the stem level, the stand level and the forest level bucking optimization problems.

At stem level, the objective is to find the bucking pattern that maximizes the single stem value. As cited by (Kevinin 2007), the dynamic programming (DP) approach is used for stem-level bucking optimization in general. But, an optimal bucking for individual stems does not lead necessarily to the same result at the stand level where we consider a large set of tree stems (Laroze 1999, Arce and al. 2002, Pickens and al. 1997), In fact, this earlier does not necessarily consider the diversity of trees in each stand, nor does it fulfil all the market constraints (desired volumes, qualities, length and minimum average small end diameter (SED) of logs). Therefore, the stand level bucking optimisation problem aims to maximize the whole production value taking into account the resources availability of the stand and the customers' needs. In order to solve the stand level bucking optimization problem, (Eng and al. 1986, Mendoza and Bare 1986, Nasberg 1985, Pickens and al. 1997) used a two stage models. In their general framework, the constrained timber procurement problem is usually modelled in the master problem and the stem bucking problem in the sub-problem. The link between the two problems and the constraints considered in each problem differ from one model to another. This method is theoretically correct and computationally efficient (Laroze 1993, Marshall 1998). But, the solution produced a large numbers of cutting instructions, which are difficult to implement by the operators of the harvesters (Laroze 1993, Martell and al 1998, Sessions and al. 1989). Heuristic approaches were proposed by (Laroze 1997, Sessions and al. 1989) to solve the same problem. (Laroze 1997) proposed a Tabu Search (TS) heuristic for each stand to generate rule-based bucking pattern for each stem class.

Forest level bucking optimization problems

At forest level, the bucking algorithms maximizing the global fit should be determined for each stand. Considering the three levels of the bucking optimization problems, the forest level is the least studied one. As an extension of his work done in 1997, (Laroze 1999) used the TS heuristic method for generating bucking rules with LP formulation to solve the forest-level bucking optimization. (Kivinen 2006) presented an extension of his work done in 2004. He found that adjusting the value and demand matrices prior to the harvesting operation was advantageous in stand level bucking. For the forest-level bucking problem, no improvement in the cumulative apportionment degree was reported by the pre-control of the price matrix.

The multi-commodity wood distribution problem

In the general theory, the multi-commodity distribution problem involves many decision problems ranging from long to short term planning. In the Strategic level, decisions on locating facilities sources are considered. Allocating customers to the supply points is an example of the decisions taken in the tactical planning level. For short term level, transportation flows and inventory levels are dressed taken into account the specific demand of each customer, the cost of transportation and inventory and others restrictions. Even there is a lot of similarities between the wood procurement planning problem and the multi-commodity supply planning problem. Similarly some differences must be taken into account: in the forest context, there is no fixed cost to the location of facilities sites (forest stand) as it is the case for others contexts. For a review of multi-commodity supply network planning, the reader is referred to (Melo and al. 2009). (Arce and al. 2002) formulated the log product allocation problem including transport activities as a Mixed Integer Linear Programming (MIP) problem. They generated the bucking pattern for this upper level MIP problem through a simple heuristic rules. Their objective aimed to maximize the total net revenue at the forest level. (Chauhan and al 2009) proposed a short term supply network planning problem in which decisions on what timber assortment should be produced in a pre-selected stands in order to fulfil the demand of some sawmills are taken. They did not address the bucking problem in their work.

PROBLEM DESCRIPTION

In the cut-to-length harvesting system considered in this project, trees are processed into the final log products at the stump, considering the demand of a set of geographically distributed mills (buck-to-order bucking problem). Two combined costs must be minimised. It is not desirable to cut many products from the same stand, mainly because it implies a reduction of the harvester productivity by 1–4% and forwarder productivity by 3–7% (Arce and al. 2002, Brunberg and Arlinger 2001, Gingras and Favreau 2002). Therefore, a non linear unit harvesting cost is considered. This cost increases according to the number of different product-mix bucked per stand and depends on the volume harvested for each product type and the bucking patterns used. The unit transportation cost, which is a significant portion of the total cost, increases linearly with the volume of transported product and depends on the distance between blocks and mills as well as the species of the product. This problem was used with three different harvesting strategies: the first one aims to apply one bucking pattern to each stand; the second aims to apply a bucking pattern for each sector (i.e., a group of stands predefined by the forest company); and the final one aims to apply a bucking pattern for each species. For each of these problems, the main question is to choose which bucking pattern to be applied to each harvesting block and in what quantities each product type (i.e., species, length) should be transported from each block to satisfy the demand of a number of different wood mills.

The main goals of this paper are, first, to analyse and propose a mathematical model for this complex problem that meets the current forest industry practice in eastern Canada, and, second, to develop solution methods that can solve large real-life problem instances in reasonable computational times. Also, we investigate the effects of the different bucking aggregation level on the harvesting cost. This is done by comparing the results of the three addressed scenarios.

CASE STUDIES

Tree species are not similar in geometry and structure. Therefore, it is inappropriate to apply the same bucking pattern to different tree species. Similarly, each forest stand represents a unique internal composition of trees in terms of species, number, size, and quality. Again, forest stands differ from one another in terms of area, density and species mixture. Consequently, applying the same bucking pattern to a group of stands may lead to a sub-optimal use of the wood source and a mismatch between demand and supply, although it simplifies the general management the harvesting operations. Therefore, in the three harvesting scenarios presented in this paper, particular attention was paid to exploring the effects of the bucking sectors aggregation level on the harvesting cost.

In this section, a mathematical formulation for each harvesting scenario is presented. The premise for theses three models is the availability of a set of bucking patterns and their corresponding product-specific timber yields. The procedure for generating these bucking patterns and their corresponding wood yields is discussed in the section 4.1. The limited number of the generated bucking patterns and the availability of the simulation tools provided by the institute of forest research in Canada (FPInnovations) are some of the criteria that motivated the choice of the following mathematical formulations of the problems. For the MIP formulation of all the problems, we consider:

$\boldsymbol{B}$ Set of harvesting blocks
$\boldsymbol{U}$ Set of mills
$\boldsymbol{P}$ Set of log/product types
$\boldsymbol{E}$ Set of species
$\boldsymbol{E_b}$ Set of species in block b
$\boldsymbol{d^L_{p,e}}$ Minimum demand (m^3) of sawmill *u* for log type *p* of species *e*
$\boldsymbol{d^L_{p,e}}$ Maximum demand (m^3) of sawmill *u* for log type *p* of species *e*
$\boldsymbol{C^t_{b,u,e}}$ Unit transportation cost between *b* and *u* for log species *e* ($dollar/m^3$)
$\boldsymbol{C^h_b}$ A crude cost for harvesting stand *b*
$\boldsymbol{V^u_p}$ The sawmill *u* unit price for log length *p*
$\boldsymbol{l_p}$ The length of product type p
$\boldsymbol{M^{b,c}_{p,e}}$ Volume of the product *p* available when bucking the species *e* of block *b,* according to the bucking pattern *c* , it is previously obtained during the simulation phase
$\boldsymbol{\gamma}$ A number < 1

Simulation of the generated Bucking Patterns

A bucking pattern is defined in our problem as a combination of at most 5 length types products from the longest to the smallest (as defined by the Canadian forest research institute *FPInnovations*). This assumption generates easy to implement bucking patterns. Table.1 shows two examples of typical bucking patterns.

Table 1: Example of bucking patterns

PatternID	StepOrder	Product	MinLen	MinDiameter
1	1	16	502	17
	2	14	440	15
	3	12	380	12
	4	10	320	10
	5	8	100	4
2	1	16	502	17
	2	14	440	15
	3	12	380	12
	4	10	320	10

The generation of the bucking pattern was done in an exhaustive way since their number is limited. *FPInterface* is used to carry out bucking simulations of the generated patterns on the considered forest data set. This software tool is specifically designed to simulate all activities in the forest supply chain. The harvesting module of this platform can predict the amount of timber assortments obtained from the application of a given pattern on a sample of trees from the cutting blocks. For the bucking pattern1 (shown in Table.1), the simulators tries to obtains as many products as possible from the first product type (1) before moving to the second one and so on. These simulations are always done once a year before the beginning of the harvesting operations, even if the output will not be used for further applications.

Scenario(1): Stand oriented bucking

For this scenario, we consider only one bucking pattern per stand (cutting site). According to this assumption, the harvesting cost can be pre-calculated. A linearized mixed integer mathematical formulation of the stand oriented wood procurement problem follows. In this formulation, the following coefficients and variables are used:

$x_{p,e}^{b,u}$ Flow of product type *p*, species *e* from block *b* to mill *u* ($dollar/m^3$)

y_c^b Binary variable: takes value *1* if pattern *c* is applied to block *b*; otherwise *0*

$K_{p,e}^{b,c}$ Binary variable: takes value *1* if the volume of product p of species e when pattern *c* is applied to block *b* is under *10%* of the total volume obtained from the bloc; otherwise 0

$C_{b,c}^h$ The unit harvesting cost if pattern *c* is applied to block *b* ($dollar/m^3$). Using the formulation giving by *FPInnovation*s, it is pre-calculated for each block *b* and pattern as follows:

$$C^h_{b,c} = C^h_b \cdot \left[\delta^Y_{c,b} \cdot \left(\sum_{p\in P} \sum_{e\in E} \sum_{c\in C} M^{b,c}_{p,e} \cdot l_p \Big/ \sum_{p\in P} \sum_{e\in E} \sum_{c\in C} M^{b,c}_{p,e} \right) \right]$$

where

δ^Y_c A correction factor addressing the number of different assortments in each block b, when using the bucking pattern *c*.

(P1) *Maximize*:

$$\sum_{b\in B} \sum_{e\in E} \sum_{p\in P} \sum_{c\in C} \sum_{u\in U} \left[V^u_p \cdot x^{b,u}_{p,e} - \left(C^h_{b,c} \cdot M^{b,c}_{p,e} \cdot y^b_c + C^t_{b,u,e} \cdot x^{b,u}_{p,e} + C^c_b \cdot y^b_c + P_p \cdot M^{b,c}_{p,e} \cdot K^{b,c}_{p,e} \right) \right]$$

subject to

$$\sum_{c\in C} y^b_c = 1 \qquad \forall\, b \in B \qquad (1)$$

$$d^L_{p,e,u} \le \sum_{b\in B} \sum_{c\in C} x^{b,u}_{p,e} \le d^U_{p,e,u} \qquad \forall\, u \in U, e \in E_b \text{ and } p \in P \qquad (2)$$

$$\sum_{u\in U} x^{b,u}_{p,e} \le \sum_{c\in C} M^{b,c}_{p,e} \cdot y^b_c \qquad \forall\, b \in B, e \in E_b \text{ and } p \in P \qquad (3)$$

$$x^{b,u}_{p,e} \ge 0 \qquad \forall\, b \in B, e \in E_b, u \in U \text{ and } p \in P \qquad (4)$$

$$y^b_c,\ K^{b,c}_{p,e} \in \{0,1\} \qquad \forall\, b \in B, c \in C, e \in E_b \text{ and } p \in P \qquad (5)$$

The problem's objective function consists in maximizing the global profit. In this objective, the first term presents the net profit of the total harvested products. The second terms gives the sum of respectively: the harvesting cost, the transportation cost, the cost of using a giving bucking pattern *c* on a giving block *b*, and a penalty term which will be described below. *Constraints (1)* says that we use only one bucking pattern per stand to harvest it. *Constraints (2)* means that the flow of product *p* of species *e*, out of stand *b* and into mill *u* must be between the lower $(d^L_{p,e,u})$ and the upper bound $(d^U_{p,e,u})$ of the demand. *Constraints (3)* states that the flow of product *p* of species *e*, out of stand *b* and into mill *u*, must respect the total supply of that product available in this stand. *Constraints (5)* is a non-negativity constraint and *Constraints (6)* states that the variables are limited to being 0/1 variables.

In practice, it is not desirable to harvest a volume of a product p, species e from a block b, that is under a certain percentage *(Ptg)* of the total volume harvested in this block. We allow this, but we penalize it using binary variables $K^{b,c}_{p,e}$. This increases the complexity of the model, since the number of binaries variables increases and the problem becomes non linear. As a first formulation, we added *constraints (6)*, which is a logical constraint supported by the commercial LP package CPLEX v12.1 to the MIP formulation (P1) and the binary variables $K_{p,e}^{b,c}$ to this constraint, as follows:

$$\boldsymbol{if((M_{p,e}^{b,c}\cdot y_c^b \le Ptg.\sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}\cdot y_c^b)\ and\ (y_c^b \ge 0))\ then\ (K_{p,e}^{b,c} = M_{p,e}^{b,c})} \qquad (6)$$

In the second formulation, we added binary variables $K_{p,e}^{b,c}$ in constraints (7) , (8) and (10) as well as $L_{p,e}^{b,c}$ in constraints (8) and (9), to the MIP formulation (P1) as follows:

$$\boldsymbol{Ptg.(\sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}\cdot y_c^b) - M_{p,e}^{b,c}\cdot y_c^b \ge Z.\left(K_{p,e}^{b,c} - 1\right)} \qquad \forall\, \boldsymbol{b,c,e\ and\ p} \qquad (7)$$

$$\boldsymbol{Ptg.(\sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}\cdot y_c^b) - M_{p,e}^{b,c}\cdot y_c^b \le Z.\left(K_{p,e}^{b,c} + L_{p,e}^{b,c}\right)} \qquad \forall\, \boldsymbol{b,c,e\ and\ p} \qquad (8)$$

$$\boldsymbol{L_{p,e}^{b,c} \le 1 - y_c^b} \qquad \forall\, \boldsymbol{b,c,e\ and\ p} \qquad (9)$$

$$\boldsymbol{K_{p,e}^{b,c} \le y_c^b} \qquad \forall\, \boldsymbol{b,c,e\ and\ p} \qquad (10)$$

where

$\boldsymbol{L_{p,e}^{b,c}}$ Binary variable used for modelling purpose, takes *1* if pattern *c* is applied to block *b*
$\boldsymbol{Z}$ Big number

Scenario(2): Sector oriented bucking

In this case, we consider only one bucking pattern per sector (a predefined set of stands). Assuming that the unit harvesting cost for each stand in the sector is pre-calculated as in Scenario1 (paragraph 4.3). The linearized formulation for the sector remains the same as in (P1), we added to it constraint (1a) only as follows:

$$\boldsymbol{\sum_{c\in C} y_c^b = |B_s| y_c^b} \qquad \forall\, \boldsymbol{s\in S, b\in B_s, c\in C} \qquad (1a)$$

where

$\boldsymbol{S}$ Set of sectors (a group of stands)
$\boldsymbol{B_s}$ The set blocks included in the sector s
This constraint specifies that the bucking pattern chosen for a sector must be the same for all stands of that sector.

Scenario(3): Species oriented bucking

For the third scenario, we consider only one bucking pattern per species of each block. In this case, the aggregated harvesting cost ($\boldsymbol{C_{b,c}^{h,e}}$) is:

$$\boldsymbol{C_{b,c}^{h,e} = C_b^h.\left[(\sum_{e\in E}\sum_{c\in C}\delta_c.y_c^{b,e})^{\gamma}.(\sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}.l_p.y_c^{b,e} / \sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}.y_c^{b,e})\right]}$$

In this scenario, it is no more possible to pre-calculate the harvesting cost as we did for the first and the second scenarios. The following formulation (P3) for the species-oriented bucking wood procurement problem is non linear. We consider:

$y_c^{b,e}$ Binary variable: takes value *1* if pattern *c* is applied to block species *e* of block b; otherwise *0*

$(\mathbf{P3})$ $\quad \boldsymbol{Maximize:}$

$$\sum_{b\in B}\sum_{e\in E}\sum_{p\in P}\sum_{c\in C}\sum_{u\in U}[V_p^u.x_{p,e}^{b,u} - (C_{b,c}^{h,e}\,.\,M_{p,e}^{b,c}\,.y_c^{b,e} + C_{b,u,e}^{t}.x_{p,e}^{b,u} + C_{b,e}^{c}\,.y_c^{b,e} + P_p\,.\,M_{p,e}^{b,c}.K_{p,e}^{b,c})]$$

$$\sum_{c\in C} y_c^{b,e} = 1 \qquad \forall\, b \in B \text{ and } e \in E_b \qquad (1e)$$

$$d_{p,e,u}^{L} \le \sum_{b\in B}\sum_{c\in C} x_{p,e}^{b,u} \le d_{p,e,u}^{U} \qquad \forall\, u \in U, b \in B\ e \in E_b \text{ and } p \in P \qquad (2)$$

$$\sum_{u\in U} x_{p,e}^{b,u} \le \sum_{c\in C} M_{p,e}^{b,c}\,.y_c^{b,e} \qquad \forall\, b \in B, e \in E_b \text{ and } p \in P \qquad (3e)$$

$$x_{p,e}^{b,u} \ge 0 \qquad \forall\, b \in B, e \in E_b, u \in U \text{ and } p \in P \qquad (4)$$

$$y_c^{b,e},\ K_{p,e}^{b,c} \in \{0,1\} \qquad \forall\, b \in B, e \in E_b, c \in C \qquad (5e)$$

As in (P1) and (P2), the objective function of the problem (P3) consists in maximizing the global profit. *Constraints (1e)* says that we use only one bucking pattern per species for each stand to harvest. *Constraints (2)* and *Constraints (4)* are common to the three models. *Constraints (3e)* states that the flow of product *p* of species *e*, out of stand *b* and into mill *u*, must respect the total supply of that product available in this stand (when we apply a bucking pattern to every species of a block). We Maintain the same penalties when we harvest a volume of a product p, species e from a block b, that is under certain percentage *(Ptg)* of the total volume harvested in this block as done in (P1) and (P2). We add to (P3), *Constraints (6e)* as a first formulation approach. For the second formulation, we also add to (P3) the same *Constraints(7e)* to *Constraints (10e)* which have the same meaning as the constraints *Constraints(7)* to *Constraints (10)* respectively in (P1).

$$if((M_{p,e}^{b,c}\,.y_c^{b} \le Ptg.\sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}\,.y_c^{b}) \text{ and } (y_c^b \ge 0)) \text{ then } (K_{p,e}^{b,c} = M_{p,e}^{b,c}) \qquad (6e)$$

$$Ptg.(\sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}\,.y_c^{b}) - M_{p,e}^{b,c}\,.y_c^{b} \ge Z.(K_{p,e}^{b,c} - 1) \qquad \forall\, b, c, e \text{ and } p \qquad (7e)$$

$$Ptg.(\sum_{p\in P}\sum_{e\in E}\sum_{c\in C} M_{p,e}^{b,c}\,.y_c^{b}) - M_{p,e}^{b,c}\,.y_c^{b} \le Z.(K_{p,e}^{b,c} + L_{p,e}^{b,c}) \qquad \forall\, b, c, e \text{ and } p \qquad (8e)$$

$$L_{p,e}^{b,c} \le 1 - y_c^{b,e} \qquad \forall\, b, c, e \text{ and } p \qquad (9e)$$

$$K_{p,e}^{b,c} \le y_c^{b,e} \qquad \forall\, b, c, e \text{ and } p \qquad (10e)$$

TABU BASED LARGE NEIGHBOURHOOD SEARCH

A Large Neighbourhood Search (LNS) is an iterative improvement approach where we modify an existing solution to the problem by making large changes. As it was reported by... , LNS is based on the fix/optimize technique (destroy/repair technique) where the fix operation corresponds to fix a subset of the solution at its current value while the rest remains variable, and the optimize method tries to improve the current solution with respect to the fixed values.

The Fix method

At each iteration, a subset of stands is chosen. All variables presenting the allocation of the bucking pattern to the species included in these stands are fixed to their current values. The fixing procedure stops when a given number of stands is selected. This number is randomly chosen at each iteration, but it cannot exceed a given number.

The repair methods

The choice of the repairing strategy is based on solution time, solution quality and diversification attributes. In this project, The optimize (repair) methods is based on a Tabu Search heuristic methods.

The Tabu Search heuristic

The Tabu Search which was proposed by Fred Glover en 1986 (Fred Glover 1986), is well performing heuristic for solving a wide variety of combinatorial optimization problems including forest management ones (Bettinger 2008 , Laroze 1999). It uses a neighbourhood search procedure to iteratively improve the initial solution, until some stopping criterion has been satisfied. Tabu list is used to direct future moves. In fact, this short term memory prevents cycling when moving away from local optima through non-improving moves. It forbids some moves likely to drive us back to recently visited solutions. The TS method range from simple designed ones to more complicated, depending on the design elements such as the nature of the Tabu tenure, the algorithm used to find initial solution and the diversification technique.

In this paper, the TS algorithm is invoked for two reasons. First, it rapidly calculates the new profit obtained from the fix step and improves it randomly and makes diversification so that the repair method does not give the same solution at each iteration. It starts with an initial solution which is the solution of the first scenario (stand oriented bucking), and tries to improve it during a total number of iterations. We consider a neighbourhood structure based on changing the allocation of a bucking pattern to every species in every move. The search is allowed to visit only feasible solutions in order to restrain the search space. At each iteration, many solutions have to be evaluated and it is important to perform this computation in an efficient way. For every new best solution in the neighbourhood found, an LP is solved to have the new transportation cost.

DESCRIPTION OF DATA

The material used for testing and evaluating each of the three scenarios consisted of 30 heterogeneous real stands in Canada. Each of these stands contains at least two of these five species: white Birch, black spruce, populus, pinus banksiana, abies balsamea (Table 2).

Table 2: Stands inventories used in the problem

Stand	EPN (/ha)	PIG (/ha)	SAB (/ha)	PEU (/ha)	BOP (/ha)	Stand	EPN (/ha)	PIG (/ha)	SAB (/ha)	PEU (/ha)	BOP (/ha)
1	54,89	112,54	0	17,47	0	**16**	55,11	78,69	2,17	62,35	0,94
2	37,90	135,70	0,9	43,80	0,3	**17**	55,11	78,69	2,17	62,35	0,94
3	57,21	42,68	2,05	12,27	1,17	**18**	55,11	78,69	2,17	62,35	0,94
4	57,21	42,68	2,05	12,27	1,17	**19**	65,88	57,66	2,97	22,82	1,73
5	57,21	42,68	2,05	12,27	1,17	**20**	65,88	57,66	2,97	22,82	1,73
6	57,21	42,68	2,05	12,27	1,17	**21**	52,75	11,39	25,29	6,61	8,12
7	58,27	63,72	0	0	0	**22**	52,75	11,39	25,29	6,61	8,12
8	58,27	63,72	0	0	0	**23**	42,49	118,23	1,02	35,6	1,16
9	58,27	63,72	0	0	0	**24**	68,56	38,42	0,06	15,52	1
10	55,11	78,69	2,17	62,35	0,94	**25**	65,09	27,84	0,03	2,59	0
11	55,11	78,69	2,17	62,35	0,94	**26**	65,09	27,84	0,03	2,59	0
12	55,11	78,69	2,17	62,35	0,94	**27**	62,88	54,06	5,6	74,11	0,67
13	55,11	78,69	2,17	62,35	0,94	**28**	62,88	54,06	5,6	74,11	0,67
14	55,11	78,69	2,17	62,35	0,94	**29**	59,04	0,04	2,54	0	0,17
15	55,11	78,69	2,17	62,35	0,94	**30**	77,85	70,82	0,28	37,23	0,29

There were 25 log-types. These types products vary in terms of species, length and small end diameter. The log specifications for each product used in the problem (for each of the five species) are giving in table3.

Table 3: Specifications of the products

Product ID	Product	Length	MinDiameter
1	16	502	17
2	14	440	15
3	12	380	12
4	10	320	10
5	8	100	4

COMPUTATIONAL EXPERIMENTS AND DISCUSSION

The models were tested with different demand instances, in order to compare the performance of the developed methods. The problems were set up with 30 bucking patterns. The size of the models differs from one scenario to another. In order to accomplish the computational tests, the algorithms were implemented using C++. The MIP and the LP problems are solved using the commercial LP package CPLEX v12.1 via its concert platform. As we deal with an annual planning, a termination criteria of a maximum running time of 24 hours was used if no optimal solution was yet found. The solution gap is fixed to 6%.

Table 4: Results for the Scenario(1)

Instances	HCost *(10^7)*	TCost *(10^6)*	Profit *(10^6)*	Time
1	2,32985	1,76617	5,897	10s
2	2,37959	1,80863	5,509	1849s
3	2,48612	1,83738	4,943	7h72
4	2,68361	1,91501	3,928	22h
5	2,38435	1,79638	5,796	207s

Table 5: Results for the Scenario(2)

Instances	HCost *(10^7)*	TCost *(10^6)*	Profit *(10^6)*	Time
1	2,337257	1,747	5,344	17h
2	2,447723	1,820	4,833	14h
3	-	-	-	-
4	-	-	-	-
5	2,442861	1,795	5,198	6h

Scenario(1) achieved better output (potential increase in the total profit), for all the instances, comparing to scenario(2). This result is not affected by changes in demand level and allocation between sawmills. We are still working on the instances 3 and 4 in (Table5) and the third part (species oriented Bucking), results and more details of the corresponding method will be presented during the conference.

CONCLUSION

The first two models proposed in this paper have achieved our goals of developing a method capable of producing a cut to length-wood procurement plan according to the actual forest practice in eastern Canada. In the solutions provided in the first two scenarios, we have in all our tests on different demand instances, registered a potential savings in harvesting costs, therefore and a substantial increase of profit. This imply that some strategic changes in the harvesting strategies, in form of applying a bucking pattern for each stand instead of sector would be very profitable. These changes will be further investigated with the third part of the project, which is the species based bucking problem. As a future research direction, one can consider an extended version of the problem to treat a (DHB) class-based bucking scenario where we apply a bucking pattern to every (DHB) tree class in each block.

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IMPROVED SKIDDING FOR SMALL-SCALE BIOMASS HARVESTING SYSTEMS

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ABSTRACT

In the quickly changing forest marketplace, new and niche markets are appearing at a rapid pace. Small-scale harvesting systems are capable of harvesting in low value biomass material with minimal footprint and capital investments. A comparison production study of two skidding machines (Turboforest TF-42C and Awassos MD-80) was performed in order to assess the economic feasibility of production levels and to evaluate the increase in productivity in regards to increasing engine power. With production values, machines could be tailored to produce a balanced harvesting system that allows for an economically feasible, small-scale production.

Keywords: Forest residue, Biomass, Feedstock, Cellulosic ethanol, small scale harvesting

INTRODUCTION

As producers face the challenges of changing social, regulatory, and market conditions, efficiency is critical to remain competitive. As the cost of petroleum based fuel rises along with concerns over the environmental consequences of their use, the demand for an alternative, renewable energy feedstock has emerged. In response to the growing outcry, governments and regulating bodies have begun enacting plans for alternative energy generation. The increased interest in woody biomass for a potential feedstock stands to create a demand for a currently underutilized product. The current state of the forested land base in the United States has the potential to provide 368 million dry tons of material toward an emerging biomass feedstock market (Perlack 2005).

The face of southern forestry has begun to shift in the past decades. The number of non-industrial private land owners possessing property with an area less than 100 acres (40.41 ha) has increased at a rate of more than 0.5 percent a year for the past three decades (DeCoster 1998). The increase in small, fragmented tracts coupled with a dominant pulp market and an emerging demand of biomass feedstock has created a need for an economic feasible harvesting system that can operate on these smaller tracts. Conventional harvesting systems that are used by the vast majority of the available producers consist of large mechanical fellers, rubber-tired skidders, and a stationary loader/processor. High transportation and capital costs have limited the size and types of harvests that these systems can operate in (Wilhoit and Rummer 1999).

The need has now arisen for an economically feasible and effective way of harvesting potential feedstock resources. Conventional harvesting systems in the southern United States are designed to maximize production and minimize cost in the near 32 million acres of plantation pine. Production in these systems decreases significantly in small diameter material. Small-scale harvesting systems (SSHS) have shown progress towards the optimization of harvesting small diameter material. Low initial capital systems comprised of small, easily transported machines have been in various forms of testing (Rummer). These SSHS also have shown significant popularity in lower site disturbance operations (Jensen and Visser 2004). However, the debate about the overall ecological benefit compared to conventional systems still continues (Marui et al. 1995).

PREVIOUS RESEARCH

A SSHS was assembled at Auburn University for the study in southern pine thinning and Appalachian timber stand improvement (TSI). The goal was to create a system comprised of readily available "off-the-shelf" products that maximized low impact production and corrected many of shortcomings of previous SSHSs. The system consisted of a 54 horsepower (40 kW) excavator based, hydraulic shear feller-buncher, a 50 hp (37 kW) grapple skidder, and a 325 hp (242 kW) drum chipper with attached loader. The initial capital investment for the system was under $300,000.

Production data was collected using MultiDAT data recorders mounted in the machines and collection of load tickets. Data was collected for the duration of the harvest of the given stands. Stand data was collected prior to harvest to evaluate product utilization and recovery. Elemental time motion studies were conducted in conjunction with production data for the identification of specific limiting factors within the system.

The system operated at a cost of approximately $88 per scheduled machine hour and was producing approximately 10 tons per hour of "dirty chips" at a loaded cost of $16.50 per ton (O'Neal and Gallagher 2008).

The previous study, however, identified a few significant problem areas that when addressed could drastically increase productivity. As identified by previous studies, it reiterated the imperative nature of operator efficiency, stand type, and pre-harvest planning on production. The skidder was also found to be underpowered and lacked the grapple size to reach proposed production rates.

STUDY OUTLINE

In an effort to compare the productivity within small-scale skidders, two different machines were evaluated and compared to existing data on the original platform. With the identification of limiting factors, the most limiting factor for production (skidder power) needs to be addressed to assess feasibility of productivity improvements. Twin extraction studies were conducted with altered platforms to evaluate productivity.

The Turboforest TF-42C skidder (Figure 1) used previously as the research platform was retrofitted with a 59 horsepower (44 kW), turbocharged power plant. The second platform that was used, a MD-80 Awassos grapple skidder (Figure 2) with an 86 hp (64 kW) engine, offered the final comparison.

Figure 1: Turboforest T42-C (Right) Comparison To Cat 525C

Figure 2: Awassos MD-80 Mini-Skidder

METHODS

Time and motion studies were conducted in field to collect gross times using continuous timing. The time collection procedure was completed using a MultiDAT recorder manufactured by FERIC. The data recorder was hardwired into the machine's electrical system to insure the MultiDAT was active during work cycles. The motion sensor threshold of the MultiDAT was set to a level that logged time in the high idle range. A Geneq SX Blue II antenna was attached to the top of the skidder's cab and wired to the MultiDAT.

Both machines that were tested operated on similar sites in southwest Alabama in conjunction with R.L. Carnes Logging Contractor Inc. Carnes produces fuel wood in dirty chip form using a balance system consisting two feller-bunchers, one skidder, and a knuckleboom loader to feed the chipper. The larger feller-buncher continued normal production while the smaller machine began bundling wood for the test machines.

The first study site (modified Turboforest machine) was located in northwest Monroe County, Alabama near the community of Franklin, Alabama. The site varied flat ground to rolling with a similar timber mix across the property. There were four landing locations during the study week, each servicing small clearcut areas. Biomass material (all growing stock excepting merchantable sawlogs) were harvested first and chipped. The merchantable sawlogs were harvested and processed. The second site (Awassos machine) was located in Coneuch County near the community of Belleville, Alabama. The study was composed of two sites one north of Belleville and one south of Belleville. Both sites were had consistent topography and timber mix. At both sites, biomass material was cut with only the large merchantable pine saw timber left.

At both study sites, the MultiDAT in each machine was setup to record a data point every three seconds when the machine was in operation. Each data point was comprised of an identification number, latitude, longitude, time-stamp, differential GPS indicator, and a speed interval. Data was also collected on the individual bundles extracted by the test machines. A field technician collected bundle data that included bundle number, stem diameter, and stem height. This is quantified using a combination of methods including the use of tracking layers in ArcGIS to "follow" the path of the machine and determine significant points of interest. Points of interest can include areas where the machine changed direction (indicating bundle location) and/or crossed certain features (entering predefined polygons can indicate a certain function). All delays will be also tallied and categorized by type. Each cycle was delineated travel empty, grapple, travel loaded, and landing time (un-grapple) as the primary elements for the extraction study. Cycle delineation metrics, found in Table 1 were used to determine cycle sampling. The analysis of the collected time data will develop a standardized cycle time.

Table 1: Operational Cycle Delineations

Element	Travel Empty	Grapple	Travel Loaded	Deck/Grapple
Beginning Action	Leave Deck Polygon	Stop at bunch	Forward movement with bunch	Enter Deck Polygon
Final Action	Stop at bunch	Forward movement with bunch	Enter Deck Polygon	Leave Deck Polygon

INITIAL RESULTS

Upon delineation, production values were first figured due to their central function in the study. Total volumes of wood (size and number of stems) were collected by hand in field and post processed. Total skidded volume is calculated in tons due to tons being the primary measure of production in the local forest industry. Productive machine hours (PMH) were calculated using the working time logged by the data recorder. Scheduled machine hours (SMH) were calculated based on the times at which the machine started for the day and parked when finished working. Defined in Table 2 and Table 3, the operational productivity varies significantly between days. This is directly associated to the turn distance between the bundles and processing site and the size of the material comprising the bundle.

Table 2: Productivity for the Turboforest TF-42 Franklin Study

	Day 1	Day 2	Day 3	Day 4	Day 5	Mean	Std. Dev
Tons	9.06	9.83	42.64	20.35	4.62	*17.30*	*15.29*
PMH	3.76	1.89	6.93	4.80	0.63	*3.60*	*2.46*
SMH	5.08	5.91	9.85	9.60	1.54	*6.39*	*3.45*
Tons/PMH	2.41	5.19	6.16	4.24	7.31	*5.06*	*1.87*
Tons/SMH	1.78	1.66	4.33	2.12	3.00	*2.58*	*1.11*

Table 3: Productivity for the Awassos MD-80 Belleville Study

	Day 1	Day 2	Day 3	Day 4	Day 5	Mean	Std. Dev
Tons	24.09	38.94	40.94	29.44	24.03	*31.49*	*8.05*
PMH	2.58	5.35	5.38	2.53	2.04	*3.57*	*1.65*
SMH	4.45	9.64	9.02	8.93	3.04	*7.02*	*3.04*
Tons/PMH	9.33	7.29	7.61	11.66	11.78	*9.53*	*2.14*
Tons/SMH	5.41	4.04	4.54	3.30	7.90	*5.04*	*1.78*

Table 4 and 5 show the increased turn production and overall maximum turn capacity in the MD-80. However, maximum turn values show similar power capabilities in the two machines if the grapple is capable of holding the volume needed to reach such weights.

Table 4: Production Capacity for the Awassos MD-80 Belleville Study

	Turns	lbs/Turn	Max. Turn (lbs)	Min. Turn (lbs)
Day 1	33	546	1,825	0
Day 2	32	661	1,979	107
Day 3	73	1,168	3,432	77
Day 4	57	714	2,337	119
Day 5	8	1,154	2,056	698
Total	*203*	*849*	*2,326*	*200*

Table 5: Production Capacity for the Awassos MD-80 Belleville Study

	Turns	lbs/Turn	Max. Turn (lbs)	Min. Turn (lbs)
Day 1	31	1,606	3,383	599
Day 2	60	1,315	3,627	317
Day 3	62	1,436	3,532	102
Day 4	43	1,355	3,050	440
Day 5	38	1,265	3,155	454
Total	*234*	*1,366*	*3,349*	*383*

Production increases, shown in Table 6 and 7, for the MD-80 can be attributed to increased pull weights and decreased turn times. A detailed exploration of the individual turns will help to determine if grapple size or engine power is the main limiting factor.

Table 6: Daily Mean Turn Data for the Franklin Study

	Day 1 n=33	Day 2 n=32	Day 3 n=73	Day 4 n=57	Day 5 n=8	Total n=203
Turn Time (sec)	423	253	342	303	284	*321*
Pull Distance (ft)*	1,715	1,690	1,040	278	653	*1,075*
Pull Weight (lbs)	546	661	1,168	714	1,154	*849*
Tree Count	12.24	17.78	9.07	20.07	10.63	*13.96*
Basal Area (sq. ft.)	0.43	0.52	0.78	0.55	0.91	*0.64*

*Pull distance is the round trip distance, not the linear distance from the landing to the bundle.

Table 7: Daily Mean Turn Data for the Belleville Study

	Day 1 n=31	Day 2 N=60	Day 3 n=62	Day 4 n=43	Day 5 n=38	Total n=234
Turn Time (sec)	323	323	315	226	193	*278*
Pull Distance (ft)*	1,401	1,175	914	678	565	*943*
Pull Weight (lbs)	1,606	1,315	1,436	1,355	1,265	*1,366*
Tree Count	11.53	16.98	13.06	16.79	15.45	*14.75*
Basal Area (sq. ft.)	1.16	0.92	1.01	0.95	0.90	*0.97*

*Pull distance is the round trip distance, not the linear distance from the landing to the bundle.

Initial turn summary data suggest that there is an issue in the power to load size ratio. The machine appears to be pulling a less than capacity load, in terms of weight, than is possible. This will be determined later with application of baseline testing. This should allow for the determination of the limiting factor, either the grapple size or machine's power. Baseline pull envelope will determine how much pulling speed is lost due to increases in pull weight, as a bundle of increasing weight is pulled over a predetermine distance.

FURTHER WORK

Additional statistical analysis and complete analysis of individual turns is needed in order to accurately quantify the differences in production. From the data collected, evaluation of differences in daily production, as well as between test machines, should provide a clearer picture of the production capacity of the machine. Initial analysis suggests that production is limited by the size of the grapple and both machines will require an increase in grapple size in order to mach the engine size.

CONCLUSION

The gross production values collected during the study period show a comparable difference in the MD-80 production and the modified TF-42. The increase demonstrates the need to effectively match grapple size to engine power. As a more detailed analysis of the individual turns is completed, a better understanding of the efficient horizon of small-scale skidding will become apparent.

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KNOWLEDGE MANAGEMENT AS A MEANS TO IMPROVE PERFORMANCE IN THE FOREST INDUSTRY VALUE CHAIN

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ABSTRACT

The forest industry has always invested considerable efforts in improving its performance in order to remain competitive. In the current business context, actors of the forestry supply chain must coordinate their actions to respond to economic, social and environmental requirements. Shared decision-making becomes inevitable and involves challenges such as the definition of common objectives and integrated planning of their forest supply chain. Also, new perspectives on performance measurements have emerged. In this context, information and knowledge become strategic resources for organizational performance. Decision makers in forestry must therefore learn to manage these intangible assets that have a direct influence on decision results, which, in turn, influence organizational and supply chain performance. In this paper we propose a knowledge management holistic approach to improve decisions performance and ultimately the overall performance of the forestry supply chain. Our results are based on a thorough literature review and an action research empirical experiment. The method was applied in the context of wood supply chain planning activities conducted by a large integrated forest products company in Canada.

Keywords: knowledge management, decision performance, forestry industry value chain, performance in forestry industry value chain

INTRODUCTION

Knowledge plays a central role in the differential competitive advantage of organizations and must be managed so as to enable knowledge workers to better accomplish their tasks and take better decisions (Drucker, 1999; Hansen *et al.*, 1999). This perception requires more from organizations than simply streamlining their operations and optimizing their resources and processes. These streamlining practices cease to contribute to the differential competitive advantage in the long-term perspective, but rather become standards of quality, compliance and measures of productivity (Lorino, 2001).

In the forestry sector the traditional concept of performance, based on productivity and efficiency, has benefited from the contribution of different methods, algorithms and mathematical models. These models and methods include various factors related to optimal resource allocation and decision-making in the forestry supply chain (Beaudoin *et al.*, 2007 D'Amours *et al*., 2008). However, despite the potential to provide solutions for complex problems encountered in forestry and the advances of these models, the resulting decisions have not been optimal in the real world.

In the current business context, actors of the forestry supply chain must coordinate their actions to respond to economic, social and environmental requirements. Shared decision-making becomes inevitable and involves challenges such as the definition of common objectives and an integrated planning of their forest supply chain (D'Amours *et al.*, 2009). Recent researches have suggested strategies, models and tools for integrated planning in forestry. Furthermore, new perspectives on performance measurements that take into account intangible assets have emerged, also in forestry context (Drole and LeBel, 2010). In this perspective, knowledge turns out to be a strategic resource for forestry supply chain performance (Mosconi and LeBel, 2010).

The main objective of this paper is to present a knowledge management (KM) holistic approach for the improvement of organizational performance (OP) based on decision performance and ultimately the overall performance of the forestry supply chain.

In this paper, we briefly present theoretical foundations that underscore organizational knowledge, its characteristics and knowledge management-related dimensions for an integrative approach. Then, we present our multidimensional and integrative framework by orienting KM towards OP based on decision performance. The theoretical and empirical results of this research work are discussed, emphasizing aspects of the contribution of knowledge based decision-making in the wood supply network. Lastly, we present some implementation aspects and partial results of our ongoing work in a forestry products company.

THEORETICAL FOUNDATIONS

Knowledge management in organizations

Knowledge is essential to the management of organizations and over the last few years has been recognized as a strategic resource for their performance (Drucker, 1999; Hansen *et al.*, 1999). KM is a management function which creates, identifies and manages organizational knowledge for long-term benefits (Darroch, 2003). It is a collection of activities that are organized and systematized to meet corporate objectives (Malhotra, 2001) and managing the knowledge resource has become an essential capability to create value within organizations (Marr *et al.*, 2004). A deeper examination of the literature on KM reveals that few studies propose an OP-oriented framework, despite the fact that reference is often made to OP in KM definitions (Ipe, 2003; Hazlett *et al.*, 2005).

Integrative frameworks that show links between the needs of the organization and strategic objectives are even more scarce (Rivard and Roy, 2005, Perrin *et al.*, 2006). However, organizations that excel in the areas of innovation and financial performance have generally, within their strategy, adopted a culture that encourages cooperation, creation and knowledge sharing, since they have recognized the value of knowledge (Rivard and Roy, 2005).

To present the framework that we propose in our work we discuss knowledge components, characteristics, and dimensions of KM in organisations for an integrative and strategy oriented framework.

Knowledge within organizations

Despite the importance of this resource, the term “knowledge” is subject to multiple classifications and several interpretations. In order for knowledge to be used effectively in organizations and improve decision performance, three components must be managed: data, information and knowledge.

The components of knowledge

Literature on KM commonly refers to knowledge components from a hierarchical view, i.e.: data, information and knowledge per se (Bhushan and Rai, 2004).. The components of knowledge can be understood along a continuum of degree of formalization as well as added value for an organization’s decisions and strategic objectives.

- Data are facts about activities. Data which are placed in context, categorized, classified, corrected and condensed constitute information
- Information is a group of data, which has meaning and can be applied in decisions that are not too complex.
- Knowledge is linked to action, the ability to generate, extrapolate and deduct new knowledge as a result of its use.

Knowledge differs from information in that it is rooted in the capacity to increase one’s ability to understand information in a given context so as to enable the creation of new knowledge (Nonaka and Takeuchi, 1995). In an organizational environment, knowledge takes these three forms, which can be represented along a continuum where the degree of codification reveals the added value of knowledge with respect to data. Knowledge must be mastered and managed in such a way that it can be read, interpreted, understood and applied by individuals to a function or a specific activity in an organization’s business processes, particularly in business decisions.

The characteristics of organizational knowledge

The value of knowledge for an organization is intrinsically related to the context in which it was created and its use. In order to fully grasp the dynamics of knowledge in an organization, its various characteristics must first be considered (Hazlett *et al.*, 2005; Quintas, 2008).

Four aspects are most often mentioned concerning decision making in the literature: it’s nature, ownership, learning and context. These knowledge characteristics affect KM in organizations. Knowledge characteristics are important to determine how to manage this knowledge and its role as a resource for the organization (Mosconi *et al.*, 2010). According to Quintas (2008), the various characteristics of knowledge reveal their inter-related nature, and this inter-related nature must be taken into consideration in knowledge management.

As well, knowledge must therefore be managed from a strategic point of view in order to enable individuals, referred to by Drucker as “knowledge workers”, to better accomplish their daily tasks and to make better decisions to meet their strategic objectives (Drucker, 1999).

KM dimensions oriented toward OP

Dimensions are determining aspects for the success of KM initiatives, practices and approaches within organizations and in order to properly manage knowledge in an organization it is essential that the characteristics of available knowledge and their different related dimensions be taken into account (Rivard and Roy, 2005). Moreover, KM alignment with strategic orientations requires an integrative framework that considers a multidimensional perspective. Rivard and Roy (2005) have stated that strategy-oriented KM needs to consider that “organization, culture and processes are determinant as information technology” [our translation] p. 30.

- Culture: defining roles and responsibilities for a sharing environment based on trust;
- Means and tools: whether or not to define or adapt tools and technological means;
- Process and activities: defining KM activities;
- The organization: defining the organizational structure to meet KM objectives.

These dimensions integrate both organizational and technological dimensions for a successful KM approach with regard to the actions required for OP (Rivard and Roy, 2005). This view is shared by Perrin *et al.*, who specify that KM must take into account a combination of technological, structural, strategic and cultural practices in order to make effective contributions to the organization. These frameworks proposed by Perrin *et al.* (2006) and by Rivard and Roy (2005) present similar visions concerning KM shortcomings and potential contribution of these frameworks of KM to OP. This suggests that literature on KM has evolved over recent years, and that KM, often criticized for its partial approaches, is making significant contributions to management theory and practice. However, most frameworks studied do not provide an overview of knowledge value and fail to establish direct links between KM and OP (Hazlett *et al.*, 2005).

Kalling (2003) conducted an empirical study where it was shown that OP is sustained by KM-related practices. Findings suggest the more integrative and holistic KM approach functions in such a manner as to use the knowledge resource for the benefit of the organization (Kalling, 2003).

KM, OP and decision performance

Holsapple (2008) affirms, “decision making is a knowledge-intensive endeavour” (Holsapple, 2008, p.21). The author also states that “To understand decisions and decision making, we need to understand knowledge and knowledge management” (Holsapple, 2008) p. 21. It is apparent that improving decision performance is a major challenge for managers in all industry sectors (Wang and Benbasat, 2009; Holsapple, 2008) and decision performance is limited by intention and the way information and knowledge is used in organizations (Wadhwa and Saxena, 2007). Furthermore, they also contribute to task achievement and the decision-making required for OP, as suggested by Holsapple (2008).

RESULTS

Theoretical results: A multidimensional KM reference framework

Our proposal is founded on a set of dimensions to facilitate KM in the organizational context, culture, processes and the technological environment. This proposal for a conceptual reference framework thus encompasses the four dimensions proposed by Rivard and Roy (2005) and Perrin *et al.* (2006): structure, culture, processes and technology and tools, illustrated and described in Figure 1. However, in order to connect the KM approach to an organization's strategy, we based our approach on the proposal by Holsapple (2008), who believes that in an organization, activities likely to create value and affect performance are related to decisions. This author stresses the importance of KM to support better decisions and to contribute to the enhancement of OP.

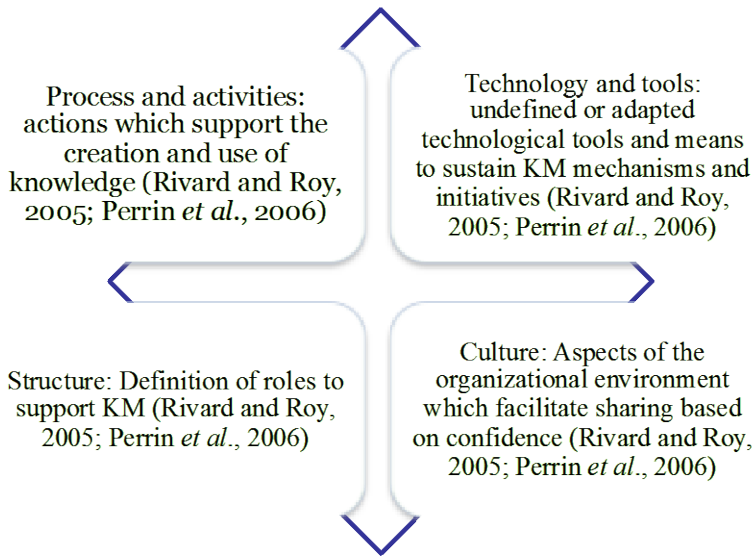

Figure 1: OP-oriented KM dimensions

In addition, Holsapple (2008) underscores the fact that a decision encompasses a body of knowledge with multiple characteristics, i.e. explicit knowledge (data, information and structured information) and tacit knowledge (insight, judgment, decision). The result of the decision is therefore composed of the knowledge available in the organization and becomes new knowledge during the decision-making process supported or not by a system. The various organizational, technological and human dimensions are essential to maximize the creation and use of the "knowledge" resource. We have adopted this view in our model, since it enables us to link the daily activities and the "knowledge" resource used to produce the decision-making results which, as a whole, should in turn support OP. This is the basis of our proposal for a conceptual framework and approach, as illustrated in Figure 2.

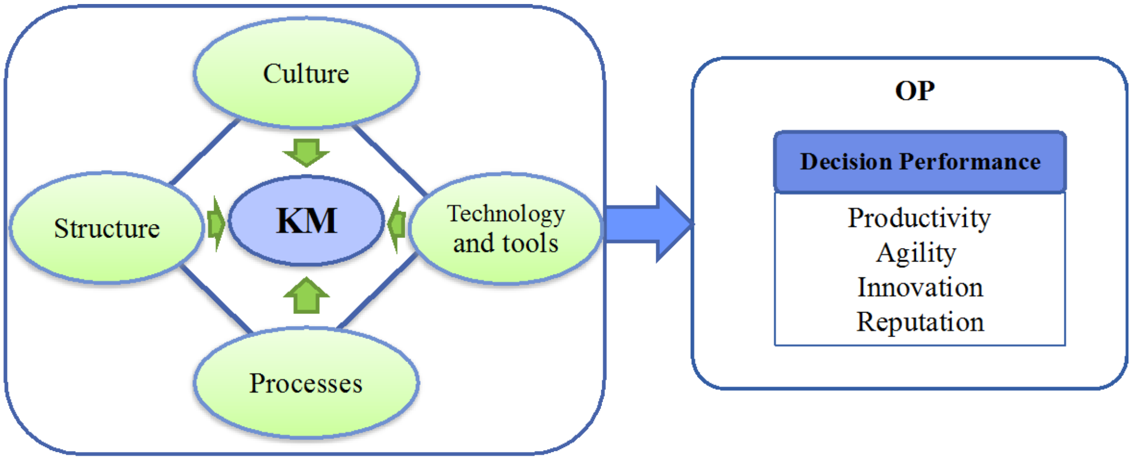

Figure 2: Multidimensional KM reference framework as a support to OP improvement

This multidimensional reference framework takes into account the knowledge available in an organization and its use in producing better decisions concerning business activities and processes regarding OP. Knowledge must be created and used to improve the decisions results in the daily tasks of individuals in order to achieve the expected KM benefits to OP. OP is measured through quantitative (objective) and qualitative (subjective) OP indicators, based on decision results and performance.

Empirical Results: KM in forestry industry products

In order to evaluate empirically our KM multidimensional framework, we adopted an action research methodology for conducting this empirical research. We developed a partnership relationship with an integrated forestry products industry, called here by the fictive name "Wood Value" and we worked together during the last three years. Action research is an iterative approach that supports researchers interventions in real organizations by proposing and working with practitioners in a transformative way (Baskerville and Myers, 2004). We adopted a five-step cycle for each research phase.

In our action research we started with a definition of common objectives and a scope of the empirical research within the organization. Managers from "Wood Value" chose the forecast of wood supply operations planning (Forecast) as a specific process for our collaborative project. Our practical research objective was to investigate how KM can support decision performance within the Forecast process and as a consequence, contribute to OP.

Improving the performance in the forestry sector has often been oriented to decision making support, particularly related to machine productivity, the optimal allocation of raw materials and other tangible resources. These advances have contributed to better understand the business and operating processes of the forest, and also investment in research and development in tools for decision support for forestry operations. Particular attention was paid to forest planning and management, due to the complexity of decisions that must be taken throughout this process central to the performance of wood supply network (WSN). Decisions made in the WSN have a significant impact on the performance of business processes, as well as the entire network of value creation in the forestry sector (D'Amours *et al.*, 2009). This is explained by the fact that the

RAF's operations represent about 50% of final product costs (PWC, 2008). Moreover, these decisions affect performance of the entire supply planning, and therefore, for the processing and other activities of the value chain of the forest industry (Beaudoin *et al.*, 2007).

We discuss with the practitioners and managers that are concerned by Forecast activities and decisions and we illustrate the context and some aspects of the complex decision making within the Forecast in Figure 3 for the Wood Value context. For "Wood Value", Forecast is a strategic monthly process that allows understanding the real state of WSN and anticipating decisions for the following months as well as predicts the main bottlenecks for the coming year.

In order to evaluate our framework we started the empirical work by undertaking a business process modelling based on the Vernadat (1996) approach and we adopted UML (Unified Modelling Language) as the formalism for our diagram representation. For knowledge mapping we adopted the CommonKADS (Schreiber *et al.*, 2004) approach to knowledge mapping and engineering. The main objective of this modelling and mapping is to better understand knowledge needs, knowledge flows, decision points and performance indicators. We combine these two approaches to map the Forecast planning process. The main steps were:

- Define processes units: activities, resources, actors and knowledge flows;
- Identify decision points: the critical decisions points, needs and goals of each point;
- Identify knowledge needs: sources (the modes of transmission, interaction and acquisition, know-how), means for storing and sharing information;
- Identify actor's role: who are the actors, their main tasks, and skills missing, the relationship between the actors;
- Formalize and represent business process: knowledge characteristics and actors.

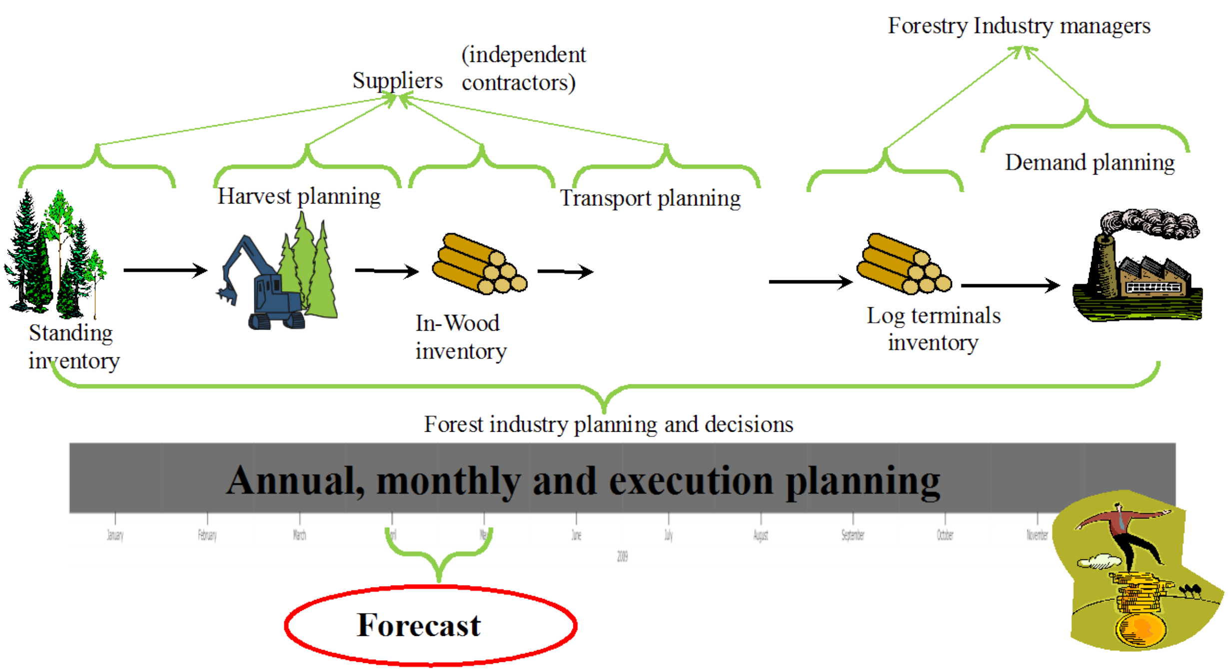

Figure 3: "Wood Value" chose the forecast of wood supply operations planning

Some statistical aspects from this mapping show the complexity and the challenges for managers and practitioners from Wood Value.

We identify that:

- 67 activities are accomplished within the Forecast process;
- 27 systems and tools (such as OR tools and other decision supports) are used;
- 23 information formats need to be processed and converted;
- 20 persons need to share information and knowledge in different decision points
- 19 decision points concerning forest operations are evaluated;
- 8 decision makers in 3 management levels participate in decisions
- 12 performance indicators are monitored.

During the workgroup sessions for knowledge mapping we identify some interesting aspects related to decision performance and some barriers for KM within the Forecast. The partial view or limited view of the decision impact along the process and the value chain is the most important problem identified. Concerning KM, the partial understanding of knowledge value, the limited comprehension of knowledge flows and the incomplete vision of knowledge available within the organization are the main challenges.

Based on our KM framework, we identify initiatives and mechanisms that can help improve KM within the Forecast. Interventions related to all four dimensions from our framework. Some initiatives supported different interventions, for example, a graphic representation of the Forecast process was presented in a focus group session with the aim of validating and sharing comprehension among managers, practitioners and us. Their feedback allowed us to propose some specific interventions in the process and activities. Also, discussion of the overview of activities allowed a shared comprehension about knowledge needs, flows and “knowledge gaps”. Moreover, the discussions benefit a better understanding of decision points and their impacts for other actors in the WSN. We have worked to implement changes and improve practices in KM to better support decision performance.

At present we have a great volume of data to analyze that comes from six interviews with people who work in the Forecast process. Our next step is a data analysis phase to know more about the perception of managers and practitioners concerning the support of KM in decision performance. Our field observation revealed that continuous efforts are needed to meet the challenges and overcome the barriers in KM and decision performance. However, we observed interesting progress in shared understanding of knowledge value and awareness in the holistic view of the Forecast process.

DISCUSSIONS ABOUT PRELIMINARY RESULTS

This paper presents theoretical and empirical results of our research work on KM oriented to OP, based on decision performance. At first, the question of KM and its tangible contribution to OP served as the motivating force behind this article. Knowledge recognized as a strategic resource for OP must be managed as an essential capability for the creation of value. However, most proposals have failed, and have not brought forth any real benefits with regard to effort in terms of performance improvement. Our results are based on a thorough literature review and an action research empirical experiment. The method was applied in the context of wood supply chain planning activities conducted by a large integrated forest products company.

A literature review was conducted to study the concept of knowledge and its various characteristics for the purpose of better understanding the concept as a strategic resource for OP and this understanding enabled us to identify OP-oriented KM approaches reported in the literature to properly define the dimensions that need to be considered in a more systemic view of KM in organizations. The dimensions identified were taken into consideration in our OP-oriented multidimensional KM conceptual framework.

In addition, we also identified an approach that enables the value of knowledge to be incorporated into organizations to improve performance. This approach is based on the use of organizational knowledge to improve the decisions results made in daily activities. We highlight the important aspect of KM to facilitate knowledge application in decision points in order to improve decision performance as foundations for OP.

Concerning empirical results, based on our multidimensional KM conceptual framework presented, our action research was guided and supported. We observed, made interventions, and proposed changes, which aimed to improve the way that knowledge was managed in the Forecast process. We observed some improvements in KM concerning the limited view of impacts of decision points and also partial understanding of knowledge needs, flows and knowledge value. Our interventions guided by the multidimensional framework supported changes in different aspects for each KM dimension, for example by modelling and mapping Forecast business process we are able to call attention to knowledge needs and streamline understanding of knowledge flows. Managers and practitioners interpret this modelling and mapping as a good opportunity to evaluate how they treat and make decisions based on their better understanding of the process. These aspects favour the adoption of new technological tools as a decision support system and facilitate their definition of problem solving. Also, managers and practitioners interviewed mentioned that Wood Value has lot of potential to better use knowledge available in the Forecast decision and to contribute to all forestry value chain.

CONCLUSION

Our findings suggest that if knowledge is mastered and managed by the individuals who will use it in a specific function or activity, or in the business processes of the organization, it can support OP and supply chain performance. Knowledge therefore becomes a true resource, as proposed by knowledge theory, and can thus be used to help meet strategic objectives and improve OP, as suggested by Grant (1996) and Foray (2004).

Decision makers must therefore learn to manage intangible assets as well as available knowledge for better decision results. Preliminary results suggest that the proposed knowledge management holistic approach for improving decisions performance (DP) and ultimately the overall performance of the forestry supply chain can support properly managing knowledge resources.

Improving decision performance is a challenge for business units in different sectors as well as in forestry. Our framework is available to support other empirical research in order to improve certain aspects and identify new ways to implement KM and support decision performance and OP. More research is needed to generate reference business models in forestry in order to facilitate the adaptation and application in different contexts where decisions are likely to be complex and can contribute to organizational performance for all actors in the value chain.

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PRODUCTIVITY AND COST OF TWO METHODS OF TRANSPORTING ENERGYWOOD FROM STUMP TO LANDING IN A TREE-LENGTH SOUTHERN PINE CLEARCUT

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ABSTRACT

There are three systems of harvesting wood for energy using conventional harvesting equipment: 1) pre-harvest systems (2-pass), 2) post-harvest systems (2-pass), and 3) integrated systems (1-pass). Past research indicates that integrated systems are most efficient in terms of both cost and biomass utilization. We conducted a designed operational study on an integrated harvest to compare the productivity and cost of delivering wood to the landing when energywood is separated at the stump and when energywood is separated at the landing. The study was conducted in a southern pine clearcut in Bertie County, NC and consisted of three treatments: 1) roundwood is felled and skidded to the landing and energywood is left standing (control), 2) energywood and roundwood are felled and separated at the stump by the feller-buncher and skidded separately to the landing, 3) energywood and roundwood are felled and skidded together to the landing and separated by the loader. Harvesting energywood reduced felling productivity by 22.3 tonnes per productive machine hour (pmh) (28%) when energywood was separated at the stump and by 12.5 t pmh^{-1} (16%) when energywood was separated at the landing compared to the control treatment. Skidding productivity per machine was reduced by 17.5 t pmh^{-1} (46%) when energywood was separated at the stump and by 9.5 t pmh^{-1} (25%) when energywood was separated at the landing compared to the control treatment. Overall, stump-to-landing costs increased by \$4.23 t^{-1} (87%) compared to the control when energywood was separated at the stump and by \$1.61 t^{-1} (33%) when energywood was separated at the landing. These results indicate significant additional costs for loggers when small-diameter stems are harvested for energy and the cost of delivering wood to the landing is higher when energywood is separated at the stump than when energywood is separated from merchantable roundwood at the landing.

INTRODUCTION

Increasing the use of wood for energy has the potential to reduce oil imports, improve sustainability, and stimulate rural economies (National Research Council 1999, Perez-Verdin et al. 2008, Alavalapati et al. 2009). Therefore, state and federal governments have enacted incentives, subsidies, and regulatory measures that promote the use of wood and other renewable energy sources. Thirty-six states and the District of Columbia have enacted renewable portfolio standards or goals that mandate or set goals for utilities to produce a certain amount or percentage of electricity from renewable sources by a target date (Database of State Incentives for Renewables and Efficiency 2011). The U.S. South has developed fewer regulatory measures and incentive programs than other states (Becker et al. 2010); nonetheless, each southern state has developed policies promoting bioenergy (Alavalapati et al. 2009).

In 2009, wood and wood-derived fuels accounted for just 1.2% of the U.S. South's electricity generation (Figure 1). However, it has been suggested that wood's contribution to America's energy portfolio, including electricity and transportation fuels, could be increased to 10% (Zerbe 2006).

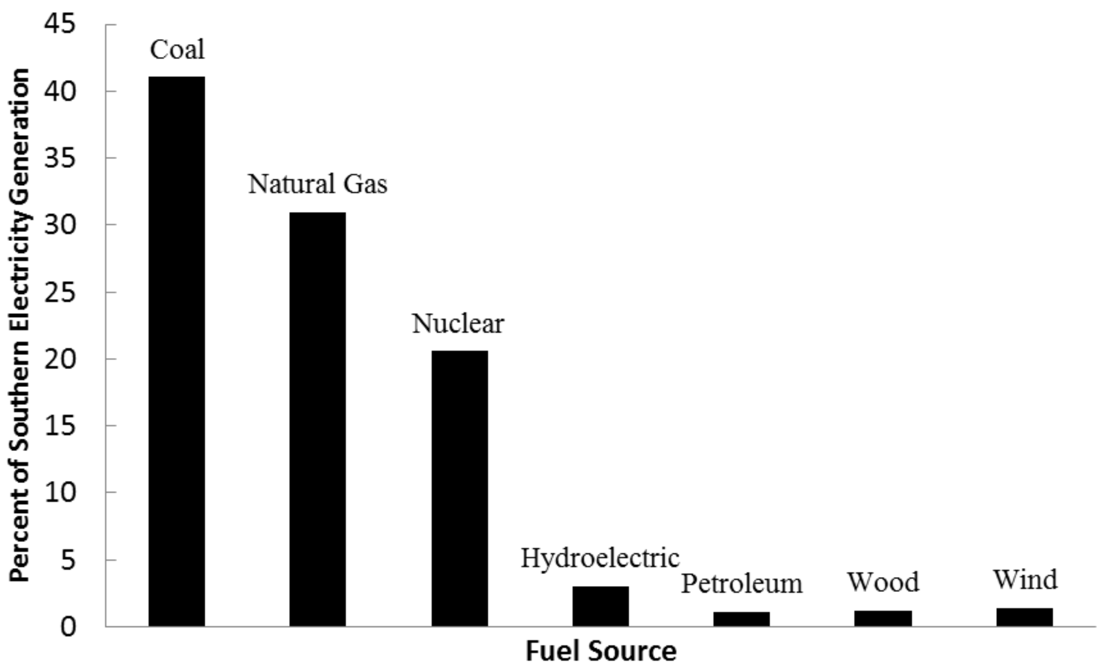

Figure 1: Electricity generation in the southeast by fuel source (Energy Information Administration 2011).

In order for wood to make significant contributions to the United States' energy portfolio, harvesting contractors must be able to economically harvest and transport energywood to processing/conversion facilities. Watson and Stokes (1989) recognized four methods of harvesting woody biomass for energy: 1) specialized machines that harvest logging slash and non-commercial stems, 2) post-harvest operations following conventional harvesting, 3) pre-harvest operations prior to conventional harvesting, and 4) integrated operations harvesting roundwood and energywood simultaneously.

Past research indicates that 1-pass systems are significantly less expensive per tonne than 2-pass systems (Stuart et al. 1981, Stokes et al. 1984, Miller et al. 1987). Stokes et al. (1984) found that the integrated approach resulted in the least cost and highest biomass utilization. Chipping costs, however, were higher for the one-pass system than the two-pass system because chipper utilization was lower. Watson and Stokes (1989) found that the cost of energywood was reduced by 30% using an integrated harvesting system compared to a pre-harvest system (\$17 t^{-1} preharvest vs. \$11 t^{-1} integrated). However, the cost of harvesting roundwood pulpwood and sawlogs was reduced following pre-harvesting (\$6-\$11 t^{-1} preharvest vs. \$9 t^{-1} integrated). Miller et al. (1987) found that the cost of energywood was 40% less using integrated harvesting compared to a pre-harvest system (\$16 t^{-1} preharvest vs. \$9 t^{-1} integrated). Post-harvesting systems are the most expensive option for harvesting energywood and typically recover less biomass than integrated systems, but typically recover more of the available biomass than the pre-harvest method (Stokes and Sirois 1989).

Within 1-pass systems, there are two ways to transport wood from the stump to the landing. Harvesting contractors can fell and skid merchantable and non-merchantable stems together and separate them at the landing. Or, they can fell and bunch merchantable and non-merchantable stems separately and skid them separately to the landing. The purpose of this study was to compare the cost, stump-to-landing, of separating energywood from merchantable pulpwood and sawtimber at the stump vs. separating energywood at the landing.

METHODS

Three replications of three harvest treatments (9 experimental units) were conducted in the Coastal Plain of North Carolina arranged as a randomized complete block design. The three treatments were: 1) a Conventional treatment in which sawtimber, chip-n-saw, and roundwood pulpwood were felled and skidded to the landing and non-merchantable stems were left standing, 2) an Integrated-Stump treatment in which merchantable and non-merchantable stems were felled and separated by the feller-buncher and skidded separately to the landing, and 3) an Integrated-Landing treatment in which merchantable and non-merchantable stems were felled and skidded together to the landing to be separated by the loaders.

This study was conducted in Bertie County, North Carolina during the summer of 2010 on a 51 ha loblolly pine (*Pinus taeda* L.) plantation. The plantation was divided into three blocks and a complete set of treatments were applied to each block. The blocks were designed so that skid distance was equal within blocks, but varied between blocks (Table 1). Blocks 1 and 3 were 22 years old, while Block 2 was 26 years old; with the exception of a portion along the boundary with Block 1 that was also 22 years old.

A preharvest inventory was conducted using fixed radius plots to estimate both merchantable and non-merchantable biomass. Merchantable stems were defined as those stems $\geq$ 10 cm in diameter at breast height (dbh) and non-merchantable stems had diameters < 10 cm dbh. Standing biomass was estimated using published weight equations (Clark et al. 1985, Saucier and Clark 1985, Clark et al. 1986, Baldwin 1987, Bullock and Burkhart 2003). Following harvest, an inventory was conducted to estimate standing and down biomass. Standing biomass was estimated as in the pre-harvest inventory, and down-woody biomass was estimated by measuring large-end diameter, small-end diameter and length of the stem within the plot for stems with a large-end diameter of at least 5 cm and a minimum length of 0.3 m. Weight of down material was estimated by determining volume using the equation of a cone and multiplying this value by previously published weight per unit volume values (Clark et al. 1985, Visser and Stampfer 2003).

The harvesting contractor observed in this study typically delivers 2,200-2,700 t per week, and is capable of wet-site harvesting. The contractor's felling and skidding equipment included one Tigercat 822C tracked feller-buncher, one 625C grapple skidder with dual tires, and one Tigercat E620C grapple skidder with dual tires.

Table 1: Harvest area (ha) within each experimental unit (treatment), total area within each block, and average skid distance (m) within each experimental unit and block.

Block	Treatment	ha	Average Skid Distance (m)
Block 1	Conventional	6.7	335
	Integrated-Stump	7.9	365
	Integrated-Landing	4.0	335
	Total	18.6	345
Block 2	Conventional	7.0	245
	Integrated-Stump	5.0	275
	Integrated-Landing	4.0	260
	Total	16.0	260
Block 3	Conventional	6.9	290
	Integrated-Stump	5.9	275
	Integrated-Landing	4.7	290
	Total	17.5	285

Felling and skidding productivity were estimated using elemental time studies. One hundred seventy-five felling cycles were observed in each experimental unit, with the exception of one that had 151 felling cycles observed. A felling cycle began when the feller-buncher dropped a bunch of stems and ended when the next bunch was dropped. Time per bunch, number of merchantable and non-merchantable stems per bunch, and delay time were recorded for each felling cycle. Felling productivity in t per productive machine hour (pmh) was calculated by dividing weight per bunch by time per bunch. Weight per bunch was estimated using weight values obtained from the preharvest inventory and the number of merchantable and non-merchantable stems per bunch.

A minimum of 25 skidding cycles were observed in each experimental unit. Time per turn, number of merchantable and non-merchantable stems per turn, skid distance, and delay time were recorded for each turn. Skidding trees from stump to landing involved two steps. First, stems were skidded to a staging area. Second, stems were skidded from the staging area to the landing. The time and skid distance for both steps were combined to estimate total turn time and skid distance. Skidding productivity (t pmh^{-1}) was estimated by dividing payload by turn time, excluding delays. Skidder payload was estimated using weight values obtained from the preharvest inventory and the number of merchantable and non-merchantable stems per turn. In the Integrated-Stump treatment, skidding productivity and cost were estimated using a weighted average productivity based on the proportion of time spent skidding merchantable roundwood and energywood.

Equipment costs were estimated using the machine rate method (Miyata 1980). For each machine we assumed a salvage value of 20% of the purchase price, economic life of 5 years, interest rate of 8% of average yearly investment, 2,000 scheduled machine hours (smh) per year, and a lube rate of 40% of fuel consumption (Brinker et al. 2002). The average hourly wage rate for logging equipment operators in North Carolina of $13.92 (Bureau of Labor Statistics 2009) was assumed for all equipment operators. Labor overhead was assumed to be 40% of the base rate (Bolding et al. 2009). Other cost assumptions are listed in Table 2. Harvesting costs (US$ t^{-1}) were estimated by combining productivity estimates with machine costs in the Auburn Harvesting Analyzer (AHA) (Tufts et al. 1985). Because we only examined the felling and skidding functions of the harvesting system, we did not constrain productivity with a system rate. Therefore, the cost of delivering wood to the landing is simply the sum of felling and skidding costs in US$ t^{-1}, assuming availability of 90% for the feller-buncher and 85% for the skidders. All costs and prices are listed in US$ and all weights are reported on a green basis.

Harvesting productivity and cost were analyzed using analysis of variance (ANOVA) and the Tukey HSD test. Statistical analysis was conducted using SAS v9.1 software (SAS Institute 2004) using the Proc GLM procedure for a randomized complete block design with three blocks and three experimental units per block.

Table 2: Machine rate assumptions used to calculate hourly costs for each piece of equipment.

Cost factors	Tigercat 822C Feller-Buncher	Tigercat E620C Skidder	Tigercat 625C Skidder
Purchase Price[a]	$400,000	$225,000	$285,000
Insurance & Taxes (% of average yearly investment)[b]	3.50%	5%	5%
Maintenance & Repair (% of Depreciation)[b]	75%	90%	90%
Fuel consumption (liters/hr)[b]	29.9	23.3	27.6
Fuel cost ($/liter)	$0.63	$0.63	$0.63
Utilization rate (%)	60%[b]	60%[b]	60%[b]

[a]Purchase prices were estimated through consultation with equipment dealers familiar with this harvesting system.
[b]Source: Brinker et al. (2002).

RESULTS AND DISCUSSION

Felling productivity was reduced by approximately 22.3 t pmh^{-1} when energywood was separated at the stump compared to the Conventional treatment (Table 3). Felling productivity was reduced by just 12.5 t pmh^{-1} when energywood and merchantable timber were felled together. One observation from the Integrated-Landing treatment was removed from the data set because productivity was unusually low, and was not representative. Overall, separating energywood and merchantable timber at the landing yielded the highest variation (Coefficient of Variation = 17%). Felling costs increased by \$0.77 t^{-1} when energywood was separated at the stump and by \$0.45 t^{-1} when energywood was separated at the landing compared to the Conventional treatment (Table 3).

Table 3: Skidding and felling cost (US\$ green t^{-1}) and productivity (green t pmh^{-1} $machine^{-1}$) with descriptive statistics.

			Productivity (green t pmh^{-1} $machine^{-1}$)			
Function	Treatment	Function Cost (US\$ green t^{-1})	Mean	Min.	Max.	Std. Error
Felling						
	Conventional	1.82[a]	77.21[a]	76.01	78.52	0.73
	Integrated-Stump	2.59[a]	54.90[a]	46.37	59.68	4.28
	Integrated-Landing	2.27[a]	64.74[a]	51.22	78.27	11.04
Skidding						
	Conventional	3.02[a]	38.02[a]	33.77	45.68	3.84
	Integrated-Stump	6.48[b]	19.35[b]	15.80	24.34	2.56
	Integrated-Landing	4.18[ab]	28.53[ab]	16.99	40.43	6.77

a,b Means not connected by the same letter are significantly different ($\alpha = 0.10$).

Skidding productivity per machine was reduced by nearly half (18.7 t pmh^{-1}) when energywood was separated at the stump compared to the Conventional treatment (Table 3). Productivity was reduced by approximately 9.5 t pmh^{-1} compared to the Conventional treatment when energywood was separated at the landing. Separating energywood at the landing also had the highest level of variability of the three treatments (Coefficient of Variation = 24%).

Skidding costs were over \$6 t^{-1} when energywood was separated at the stump, compared to just over \$3.02 t^{-1} in the Conventional treatment, an increase of 114% (Table 3). Skidding energywood and merchantable stems separately increased the number of passes required compared to the other two treatments because of very low payloads when energywood was being skidded. Skidding costs were 38% higher when energywood was separated at the landing compared to the Conventional treatment. Even when handling energywood and merchantable stems together, skidder payload was still reduced compared to the Conventional treatment, and this reduced productivity and increased costs.

Overall, stump-to-landing costs were \$4.84 t^{-1} in the Conventional treatment, \$9.07 t^{-1} when energywood was separated at the stump, and \$7.66 t^{-1} when energywood was separated at the landing. These data suggest important increases in harvesting costs when large wet-site loggers attempt to harvest energywood. Low skidder payloads, especially when energywood was separated at the stump, reduced skidder productivity and significantly increased costs. These data suggest that harvesting contractors that produce energywood in an integrated system should separate roundwood and energywood at the landing rather than at the stump. However, this will reduce loader productivity and loggers may not be willing to risk increasing truck turnaround time as a result. This study did not quantify the reduction in loading productivity when handling energywood.

Separating energywood at the landing vs. the stump did not make a significant difference in biomass utilization. Residual woody biomass following the Conventional treatment was 18 t ha^{-1}, compared to 4 t ha^{-1} when energywood was separated at the stump, and 3 t ha^{-1} when energywood was separated at the landing.

CONCLUSION

This study documented important felling and skidding cost increases when harvesting woody biomass for energy. These increases were amplified in this study because of expensive equipment that burned more fuel than the equipment used by many harvesting contractors. Past research by Westbrook et al. (2007) and Baker et al. (2010) suggests that loggers with lower capitalization and more fuel efficient equipment can harvest energywood in an integrated system more profitably than the logger observed in this study.

Past research indicates that harvesting energywood in an integrated system is less expensive than pre-harvest and post-harvest systems (Stuart et al. 1981, Stokes et al. 1984, Miller et al. 1987). For harvesting contractors harvesting energywood in an integrated system, this study suggests that costs can be reduced by felling and skidding merchantable roundwood and energywood to the landing together and separating the energywood at the landing. Furthermore, this study found that residual woody biomass does not differ following the two approaches. Nonetheless, separating energywood at the landing will reduce loading productivity, and some harvesting contractors may be hesitant to risk increasing truck turnaround time. This study only examined stump-to-landing costs, and depending on the system being observed, reductions in loading/processing productivity may or may not be of concern. For example, if the loading function is underutilized when handling only merchantable stems, then reducing loading productivity would not significantly increase system costs.

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CUSTOMER-PERCEIVED VALUE IN FOREST HARVESTING OPERATIONS

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ABSTRACT

The measure of performance in forest harvesting is an essential prerequisite for planning and improving forest operations. Traditionally the focus has been towards machine-related performance measures such as production of wood per time unit. However, in today's increasingly complex wood supply networks, the demand of a more complex analysis of performance is on the rise. This study develops a method for evaluation of harvesting contractor performance and applies it in performance analysis of a large contractor dataset. The service management theory of customer-perceived value was used as a framework in a series of interviews with forest company officials in order to identify key indicators of performance that affect the harvesting service' value to the customer. Interview results reveal the complexity of harvesting operations and points out several important aspects of harvesting contractor performance. A questionnaire that measured the identified aspects was developed and used by five forest company production managers in their assessment of the perceived value of their employed contractors' services, which resulted in 74 assessed entrepreneurs in total. The questionnaire also measured how the production managers perceived the importance of each aspect. A main conclusion is that the largest potentials for improving the contractors' customer-perceived value is connected to timber and thinning quality, management, cooperation with forest company, productivity and machine utilisation. Such improvements, if realized on a broad scale, are likely to improve the function of the whole wood supply network.

Keywords: Customer-perceived value, harvesting, contractors, survey

INTRODUCTION

Many Swedish forest companies outsourced most of their harvesting operations to small contractors during the 1980's and early 1990's. These contractors were often recruited among the forest companies' own employed machine operators who were offered to buy their machines from the forest companies and continue as more or less independent contractors (Hultåker 2002, 2006). The outsourcing introduced a new interface in the wood supply system which put both forest companies and the usually recently started contracting businesses in totally new roles as customers and suppliers of harvesting services. This study will investigate the nature of this relationship and try to quantify to what extent the contractors manage to create value for their customers using the theory of customer-perceived value (CPV).

Ravald & Grönroos (1996) define the customer-perceived value of a service as the customer's perceived benefits from the service in relation to the customer's perceived sacrifice needed in order to gain these benefits. Grönroos (1997) discussed this further in another article and developed the definition of CPV into a model well suited for analysis of the relations between harvesting contractors and forest companies. He argues that the CPV of a service can be regarded as a function of four main components; core solution, additional services, actual cost and relation costs (Equation 1).

$$[1] \qquad \textit{Customer Perceived Value} = \frac{\textit{Core Solution} + \textit{Additional Services}}{\textit{Price} + \textit{Relationship Costs}}$$

- *Core Solution* describes the physical outcome of a service in technical terms.
- *Additional Services* describes other immaterial values of a service that the customer benefits from such as delivery, claims handling, etc.
- *Price* describes the monetary cost of a service.
- *Relationship Costs* can be direct costs for maintaining the business relation, such as costs for administration or computer systems, but also includes indirect costs, caused by delivery problems for instance, and psychological costs, caused by the customer's fears that the service will not function as promised.

However, in order to analyse the customer-perceived value of harvesting contractors' services, the rather generic model needs to be put into a forest operations context and expanded into a concept of measurable aspects of perceived value. This study will use the generic CPV model as a conceptual framework and expand it with a set of forest harvesting specific subaspects. The goal is not to quantify CPV as such but rather to describe forest company officials' perceptions of the importance of various CPV subaspects and how well harvesting contractors perform in those. The described below will be used in studies in the future in order to gain a deeper understanding of CPV in a harvesting operations context.

METHODOLOGY

In this study we have focused on the Swedish forest company SCA as customer and a group of harvesting contractors employed by SCA as service providers. SCA's harvesting contractor relations are managed by a group of five production managers who acts like hubs in a large integrated network supplying SCA's own industries with timber and are responsible for contracting harvesting resources in their respective geographical areas. The 74 contractors included in the study were all employed on a long term basis by the production managers during the period 2007-2009. Most of the contractors had been working with SCA as the only customer of their services for several years.

Another group comprising a chief technical officer, a production manager who had acquired his office after the study period's end, an improvements manager and a production supervisor were formed in order to participate in the identification of CPV subaspects. The group of interviewees was selected because they had very good insights in SCA's contracting of harvesting resources. The interviewees were first asked to reflect on Grönroos' (1997) four CPV aspects and elaborate on their meaning in the relation between forest company and harvesting contractors. Secondly a gross list of subaspects were compiled and sent back to the interviewees for comments and then reworked until all interviewees agreed on a common set of subaspects (Table 1).

The identified subaspects connected to the price aspect were all possible to measure accurately in SCA's production follow-up systems, whereas direct measurements for the other subaspects were lacking. This called for the development of a questionnaire designed to measure the production managers' perceptions of each contractors' services. The questionnaire (Table A1) comprised between one and three 10-graded Likert scale questions per CPV subaspect and was designed so that a high mark on any question would indicate a positive contribution to CPV. The 10-graded Likert scale format was chosen in order to encourage variation in the answers (DeVaus 2002). Subaspect scores is calculated from the questionnaire by taking the mean value of the questions associated with a certain subaspect. The finalised questionnaire was tested on two of the interviewees which revealed the need for some minor adjustments. The production managers were then asked to complete a questionnaire for each of their contractors. Additionally the production managers were asked to mark how important they found each subaspect to be on a 10-graded scale.

RESULTS

The interviewees of this study identified *Timber quality, Thinning quality* and *Environmental considerations* as the three most important aspects of the contractors' core solutions. Timber quality refers to how well the produced logs correspond to current bucking and sorting instructions and to what extent the contractors are causing unnecessary timber value losses due to log end checks, feeder roll slip, etc. Thinning quality is defined as the contractors' ability to meet demands on strip road width and spacing, thinning strength, residual stand damages etc. Since the harvesting contractors are responsible for taking appropriate Environmental considerations on their harvesting sites and thus for the operations' compliance with various environmental standards[1], it is of vital importance that they harvest according to all the demands stipulated in the certificate regulations.

In a complex supply network with minimised roundwood stock levels, *Flexibility* – the ability to respond to changes in the company's needs and to solve problems independently as they arise – and *Delivery performance* – the ability to deliver agreed volumes on time – are highly desirable contractor features for efficient operations. Long term contractor relations mean that it is imperative for the development of the supply network that the contractors take actions on their own to improve their effectiveness. The interviewees divided this ability to improve operations into two subcategories; *Management,* which is defined as the ability to constantly optimize and improve the contractors' own operations, and *Cooperation* focus, which is defined as the ability to initiate improvements and embrace suggestions on improvements of the company-contractor relationship.

The price of different contractors' harvesting services is difficult to compare since they are operating under different conditions. In order to assess the cost competitiveness of the

[1] SCA is certified according to FSC and ISO14001 standards.

contractors without comparing the actual prices, the interviewees suggested that two subaspects should be used for harvesters and forwarders; *Utilisation rate* and *Productivity* in relation to a productivity standard.

When asked to elaborate on relationship costs the interviewees pointed out efficient and accurate *Daily communication* and an easily maintained *Business relationship* as two desirable features of the company-contractor relationship. Table 1 gives a schematic overview of the identified subaspects and their relations to the main aspects of CPV.

Table 1: Descriptions of the identified subaspects of customer-perceived value.

Aspect	**Subaspect**	**Description**
Core solution	Timber quality	Bucking, sorting, timber damages, etc.
	Thinning quality	Damages to residual stand, strip road width and spacing, thinning strength, etc.
	Environmental considerations	Compliance with certification regulations, minimized soil damages etc.
Additional services	Flexibility	Geographically flexible, adapts production rate to the demand, solves problems independently, etc.
	Delivery performance	Delivers agreed volumes on time.
	Management	Makes efforts to improve his own efficiency, develops the personnel, etc.
	Cooperation	Makes efforts to improve cooperation with the customer.
Relationship costs	Daily communication	Gives daily production reports in the stipulated manner, alerts the customer when encountering problems, has a keen ear to the customer's needs, etc.
	Business relationship	Smooth annual negotiations, easy to come to agreement with on piece rates, additional payments, etc.
Price	Harvester productivity rate	Harvester productivity in relation to a productivity norm.
	Forwarder productivity rate	Forwarder productivity in relation to a productivity norm.
	Harvester utilisation rate	Harvester productive machine time (PMH) over computer uptime
	Forwarder utilisation rate	Forwarder productive machine time (PMH) over computer uptime

Perceptions of contractor performance

Table 2 summarizes some descriptive statistics on how the contractors score on the various CPV subaspects. Contractors who exclusively worked in final fellings did not get marked on thinning quality and contractors who were ordered to produce at their maximum capacity at all times did not get marked on delivery performance. Notably, one of the production managers had ordered all contractors at his disposal to always produce as much as they could.

On average the production managers assessed the contractor's performance on the subaspects slightly above 7, with subaspects Management and Cooperation scoring slightly lower. The largest standard deviations in scored subaspects appeared in thinning quality, delivery performance and cooperation.

The contractors in the study produced on average 4 % more wood than was predicted by the productivity standard, but the differences between individual contractors were very large. The most productive contractor exceeded the standard by more than 40 % while the least productive contractor only reached about 73 % of the production predicted by the standard, with a standard deviation of 14 % for all contractors. Average machine utilisation rate was about 83 % with a standard deviation of 6 %. As with the productivity rate, there were large differences in machine utilisation among the contractors. In fact the least utilised forwarder only forwarded 55 % of the time the machine was available and the machine computer turned on, while the most utilised harvester reached a very impressive utilisation rate of 97 %.

Table 2: Subaspects of customer perceived value scored or measured for 74 contractors during the period 2007-2009.

Aspect	Subaspect	n	Mean	StDev	Min	Max
Core Solution	Timber quality	74	7.2	1.4	4.0	10.0
	Thinning quality	44[a]	7.1	2.1	1.0	10.0
	Environmental considerations	74	7.4	1.2	5.0	10.0
Additional Services	Flexibility	74	7.0	1.3	3.0	9.3
	Delivery performance	44[b]	7.0	2.0	2.0	10.0
	Management	74	6.5	1.6	2.3	9.0
	Cooperation	74	6.1	1.9	1.0	9.7
Relationship Costs	Daily communication	74	7.7	1.4	3.0	10.0
	Business relationship	74	7.2	1.4	2.0	10.0
Price	Harvester productivity rate[c]	74	1.05	0.14	0.73	1.44
	Forwarder productivity rate[c]	74	1.03	0.14	0.72	1.43
	Harvester utilisation rate[d]	74	0.82	0.06	0.66	0.97
	Forwarder utilisation rate[d]	74	0.84	0.06	0.55	0.96

[a] 30 contractors with large machines were only involved in final felling operations.
[b] 30 contractors were ordered to always produce as much timber as they could manage which makes an assessment of their delivery performance irrelevant.
[c] Actual productivity during the period divided by expected productivity according to a productivity standard.
[d] Productive machine time (PMH) during the period divided by machine computer uptime.

Perceived importance of CPV subaspects

The production managers graded subaspects connected to the Core solution on average around 9 on the 10-graded importance scale while the other subaspects were graded around 8. The exception from this was Delivery performance which got the lowest average mark of 5 (Figure 1). Delivery performance also contains the largest differences in perceived importance; the five production managers marked it, respectively, 9,7,6,2 and 1, which indicate that there are two quite opposite opinions within the group. Perceptions of Management and Cooperation importance also cover fairly large ranges.

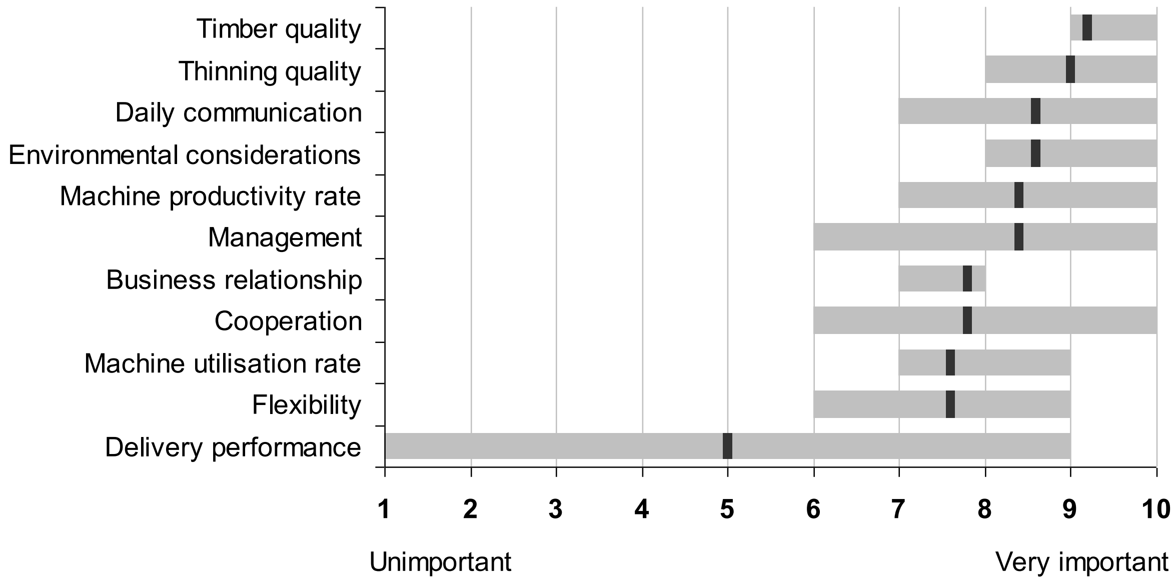

Figure 1: Subaspect importance according to the five production managers (black bars indicate the mean value, whereas grey bars are the minimum-maximum range).

A low price of the harvesting service will always be of interest for the customer, but which other aspects or subaspects of CPV that is most important to improve is more difficult to determine. In Figure 2 the importance assessed by the production managers for each non-price related subaspect is compared to the contractors' average score. Large discrepancies between perceived importance and average scores given to contractors were observed for subaspects Timber and Thinning quality, Management, Cooperation and Delivery performance.

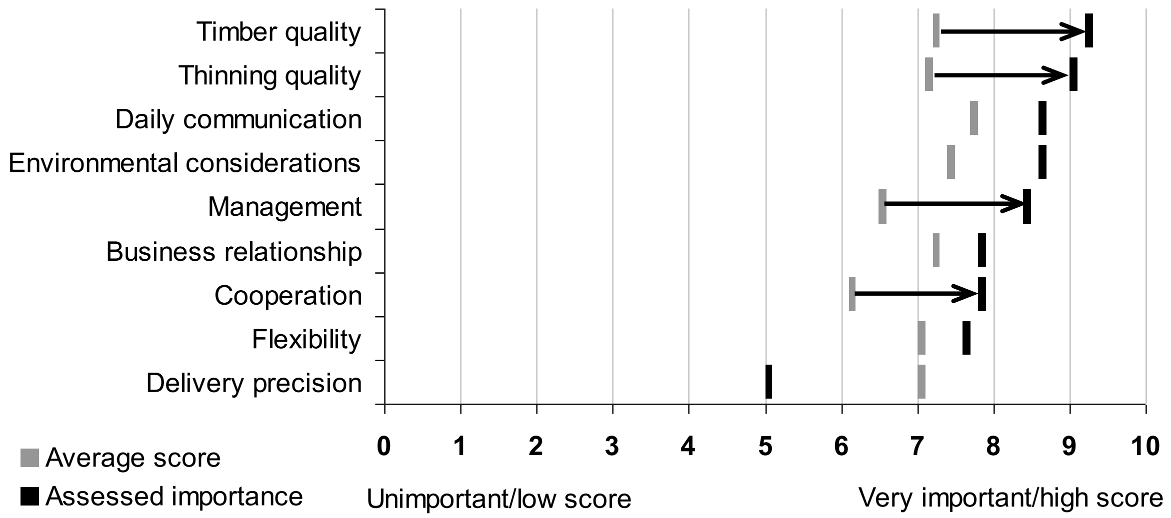

Figure 2: Assessed subaspect importance and average contractor scores. Arrows represents large possible improvements.

CONCLUSIONS

Contracting forest harvesting services might seem like a fairly simple business at first glance, but this study has revealed that it can be described as a multi-faceted operation that require high performance in a number of fields in order to keep the customer happy. The contractors in this study managed fairly well in this and on average scored quite high even though the variation in some of the identified subaspects was large.

Most production managers considered all subaspects to be fairly important which indicates that, overall, the study was successful in the subaspect identification process and that the suggested model should be well suited for further analyses of CPV in harvesting operations. A notable exception was two managers who graded Delivery performance as unimportant. This could indicate that these two are managing their contractors in a way that lessens the need for controlling deliveries from individual contractors. The same thing is implied by the fact that 30 of the 74 contractors worked under the order to constantly deliver as much timber as they could manage while the deliveries from the other 44 contractors were more or less closely monitored and managed by the production managers. The possibility that harvesting resources likely are managed in different ways by the production manager's call for further research and analysis. If the requirements on Delivery performance could be lifted for a larger proportion of the contractors through more efficient management they probably could put more focus on improving their performance in other fields, such as for instance Timber quality or Productivity.

Large discrepancies between perceived importance and average scores were observed for five subaspects, but since the perceived importance of Delivery performance cover such a large range it is unadvisable to draw any conclusions from that discrepancy. However, the remaining four subaspects with large discrepancies indicate possible improvements of CPV which should be prioritized by both contractors and forest company in order to improve their business relationship. The large variation in Productivity and Utilisation rate indicate possible improvements in those aspects as well and call for further research in order to investigate the underlying causes of variation and identify possible actions to improve the contractors' performance.

This study was conducted within a single forest industry company which makes it advisable to use some caution before making generalizations of the results. However, the number of contractors included in the study was quite large and the five production managers were facing different supply situations in their respective geographical areas which ensure that considerable variation is included in the studied material. This makes it safe to assume that patterns like the ones outlined in this paper exists in similar relationships between other harvesting contractors and wood procurement organizations as well.

The theory of customer-perceived value offers an attractive conceptual framework for the analysis of customer-supplier relationships. Possible further studies of CPV in a harvesting services context could include, for instance, analysis of correlations between various CPV aspects and contractor profitability.

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APPENDIX

Table A1: The questionnaire used for assessing the production managers' perceptions of the identified subaspects of customer-perceived value (translated from Swedish).

Aspect	Subaspect	Question[a]
		How happy are you with the contractor's;
Core solution	*Timber quality*	product quality?
	Thinning quality	thinning quality?
	Environmental considerations	environmental considerations?
		How much do you agree to the following statements;
Additional services	*Flexibility*	The contractor adapts his production rate to the company's needs.
		The contractor is geographically flexible if needed by the company.
		The contractor solves problems in a suitably independent manner.
	Delivery performance	The contractor delivers agreed volumes on time.
	Management	The contractor train and develop his personnel.
		The contractor uses equipment well suited for the task at hand.
		The contractor is constantly trying to improve his business.
	Cooperation	The contractor gives suggestions on possible improvements of the cooperation with the company.
		The contactor carries through suggestions on improvements from the company officials.
		The contractor's commitment helps the company to improve its operations.
Relation costs	*Daily communication*	The contractor communicates well with company officials.
		The contractor is receptive to information from the company and informs his/her staff.
		The contractor reports his daily production in the agreed manner.
	Business relationship	It is easy to negotiate new contracts with the contractor.
		It is easy to reach agreement with the contractor regarding rates, extra compensations, etc.
		The contractor controls and guarantees his/her own delivered quality.

[a] Respondents were asked to give their answers on a 10-graded scale where 1 equalled very unhappy or strongly disagree and 10 equalled very happy or strongly agree. The questionnaire was constructed with the intention that high marks always should be a positive indication for customer-perceived value.

EFFICIENCY OF BIOMASS HARVESTING IN POOR QUALITY STANDS OF EUCALYPTUS IN WESTERN AUSTRALIA

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ABSTRACT

Using forest biomass to generate energy has been started in recent years in Australia. There is a pelletizing plant in Western Australia which utilizes some of the forest biomass as source of energy. In this project, a poor quality stand of Eucalyptus with small tree size was harvested with a tracked Tigercat feller buncher. Then the whole trees where extracted by grapple skidder. A chipper was used to chip whole trees into containers of the trucks. Time study method was applied to collect the data to evaluate the production rates for the machines of biomass system. Working delays were recorded in three categories; personal, mechanical and operational delays. Using the multiple regression approach a productivity predicting model was developed. Skidding distance and load weight were significant parameters affecting the productivity of grapple skidder. The results of analysing productive and non-productive time of the equipments indicated that the percentage of the working delays are relatively high which requires more appropriate logistic management. Finally the biomass yield per area and per ha was evaluated which can be used for biomass supply chain management.

Keywords: Biomass, productivity, feller-buncher, skidder, chipper

INTRODUCTION

In conventional logging, the stem of trees is usually utilized, and may only contain about two-thirds of the tree volume with the remaining one-third left in the field or at roadside. Thus the residues from conventional logging can be used in biomass harvesting (Karjalainen et al. 2004). Dedicated energy crops are another source of woody biomass for energy. Short-rotation (3-15 years) techniques from growing poplar (Populus), willows (Salix) and Eucalyptus or even non-woody perennial grasses have been developed over the past 2-3 decades. Harvesting usually occurs in the winter and the harvested stems are often converted to chips on the site and then transported to the conversion plant (IEA Bioenergy, 2002).

Studies in many countries show that crown mass removal may endanger the sustainability of production capacity, depending on the site characteristics and amount and composition of removed biomass. However, field experiments usually incorporate uniform distribution of material after logging in control plots and complete removal of crown components from whole-tree logging plots (Kuiper, 2006).

Negative ecological impacts can be reduced by appropriate timing of operations, minimizing the nutrient removals from the forest sites and recycling of ash from the combustion installation. These methods will not completely compensate the nutrient loss, but will certainly reduce it. The removal of forest residues from poor sites should be avoided in all cases, because this would further reduce the nutrients availability in these already nutrient poor sites (Burgers, 2002; Hakkila, 2002).

In Scandinavian countries a significant proportion of their harvest is from ground-based systems, which are highly mechanized. These have in many areas had their work methods adjusted to leave the logging residue in piles (as opposed to spread out) to enhance the efficiency of the residue harvesting operation. Chipping can be operated in following places; at mills, at storage yards, at forest roadside or in the stand (Kuehmaier et al. 2007). In Denmark in stand chipping is often used in thinning and small tree diameter harvests (Talbot and Suadicani, 2005). The felling and bunching of trees is carried out by a feller-buncher in the extraction corridors. After being dried for about 20 weeks, the material is chipped in the stand and transported to the road side with an integrated container, or with machines carrying separate containers. Then the materials are transported to the plant with truck containers. Silversides and Sundberg (1989) suggested that the greatest advantage may be realized in chipping of multiple stems simultaneously. In this case the chipper is less susceptible to the negative cost-effects of the »piece-volume-law« (which states that increasing piece size typically results in increased production).The most common option in the production of woody biomass is chipping at the forest roadside and transportation of chips. About 70% of the annual woody biomass production in Finland is produced in this way (Ranta and Rinne, 2006; Junginger et al. 2005).

Using forest biomass to produce energy is just starting to be explored in Australia. There are some woody biomass utilization programs including power stations that co-fire wood waste with coal, at Delta Electricity in Wallerawang, Vales Point and Mount Piper (NSW), Macquarie Generation at Liddell and Bayswater (NSW), Envirostar's Stapylton (QLD) and Western Power's Muja power stations (MBAC, 2003). Plantation energy pelletizing plant in Albany, Western Australia is being commisioned to use forest biomass.

With emerging opportunities in Australia to use forest fibre in energy uses like wood pellets and heat to energy plants, some land owners are considering this market option for plantations with limited returns from current pulp chip markets. Part of this decision is driven by an expected savings in the harvest cost for the lower quality chip product, this study evaluates harvest productivity and costs in a very low productivity mixed hardwood plantation to be used as biomass in a pelletizing plant.

STUDY AREA AND HARVEST SYSTEM

The study area was a low productivity mixed Eucalypts mainly *E. GXC hybrid* located at Quindinup WA (table 1). The stand was not economically viable to harvest for export pulp chip so was harvested with full-tree chipping as a supply to a pellet plant.

The harvesting system (Figure 1) included a tracked feller-buncher (Tigercat 845C), grapple skidder (Tigercat 730C) and mobile chipper without delimber/debarker (Husky Precision 2366) to maximise biomass production.

Table 1: Study area description

Area (ha)	5.2
Stand density (n/ha)	637
Average DBH (cm)	14
Average tree size (tn)	0.100
Terrain	Flat

Stand	**Skid trails**	**Landing/forest road**
		
Tigercat 845C feller-buncher	***Tigercat 730C skidder***	***Husky Precision 2366 chipper***

Figure 1: Biomass harvesting system

STUDY METHOD

Standard CRC Forestry time and motion study methods were used and total production was measured through truck weights of the total biomass delivered to the client. Productivity is calculated on an as-received tonne both on PMH_0 (excluding all delays) and PMH_{15} (including delays up to 15 minutes). Work delays were classified into three categories; personal, mechanical and operational delays. The reason for any down time was noted during time study. Working cycle for skidder contained of travel empty, loading, moving during loading, travel loaded, unloading and clearing debris.

RESULTS

Table 2 shows a low productivity for feller-buncher and chipper, which is a result of the small tree size in the study area.

Table 2: Summary of production rates of biomass operation

Machine	Production (tn/PMH_0)	Production (tn/PMH_{15})
Feller-buncher	50.1	47.9
Skidder	44.6	37.1
Chipper	50.8	44.8

The productivity models for the skidding (Figure 2 and 3) show, as expected, decreasing productivity as the snig distance increases and increasing productivity with increasing payload.

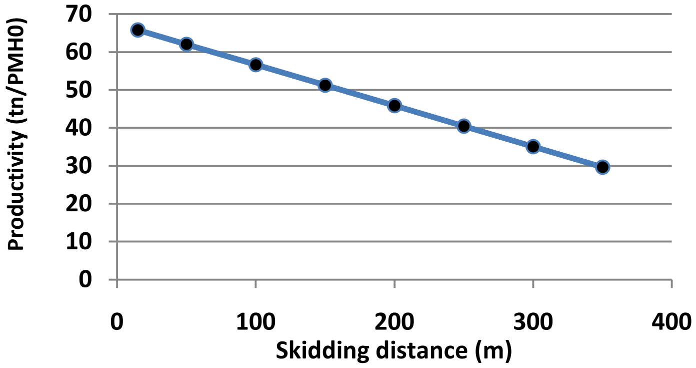

Figure 2: Skidding productivity vs Skidding distance (for average load of 3.02 tn)

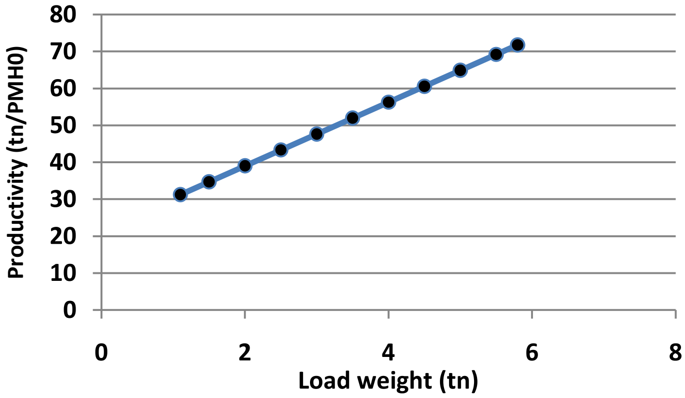

Figure 3: Skidding productivity vs Load weight (for average distance of 182 m)

The harvest delivered 63.9 tonnes per hectare based on the recorded load weight of 7.5 trucks (Table 3). It must be noted that the biomass weight was recorded between 7 & 8 days after harvesting.

Table 3: Biomass production summary from study area

Total harvested biomass (tn)	332.13
Area (ha)	5.2
Biomass yield (tn/ha)	63.9

Figure 4 and 5 shows the feller-buncher was productive 79% of the total harvester time. Of the 18% lost to long delays (>15 min.), service time comprised (19%), supervisory meeting (17%) and 64% for meal break. Short delays (<15 min.) included idling time, task planning and taking breathers.

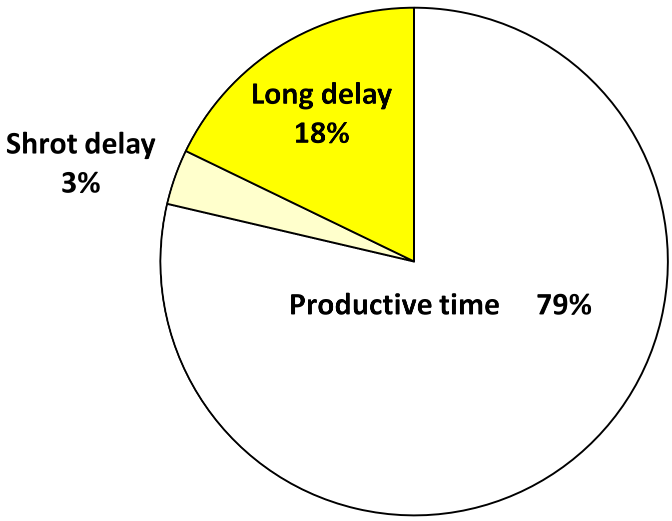

Figure 4: Working times for feller-buncher

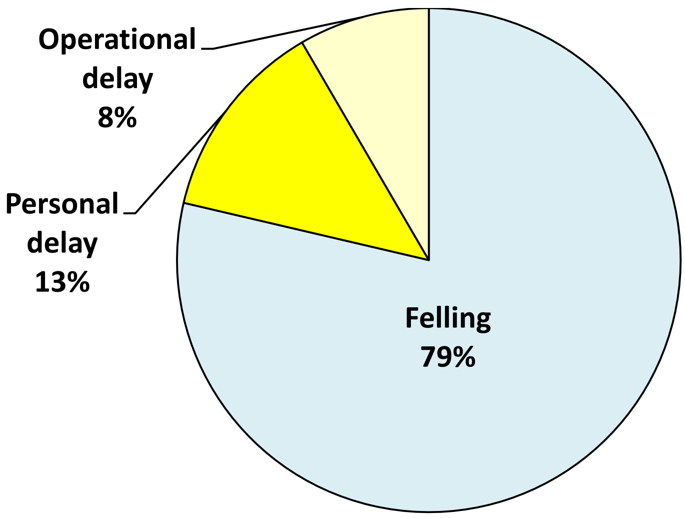

Figure 5: Percentage of work time elements and delays for feller-buncher

Figure 5 shows skidder was working productively 59% of the study time (6% of time was debris cleaning). Figure 6 provides the proportion of time spent in each work element too.

Almost all of the short delays involved waiting for the chipper. Had the skidder staged these loads and left to extract another load, chipper productivity may well have dropped through increased time waiting for wood.

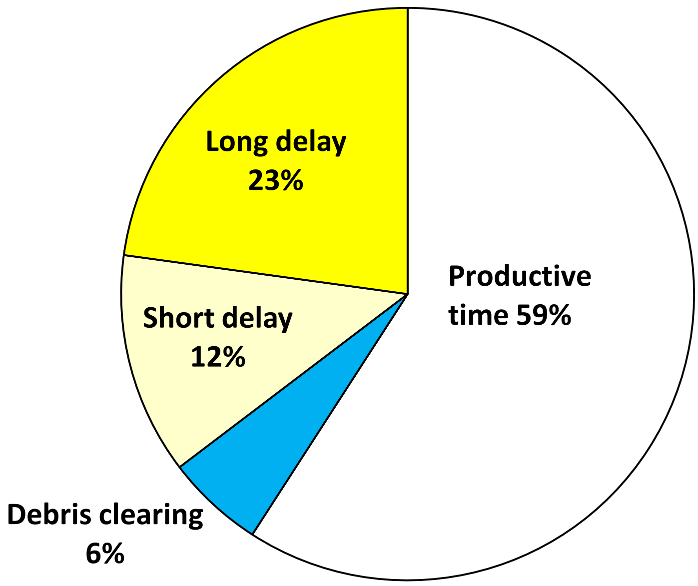

Figure 6: Working times for skidder

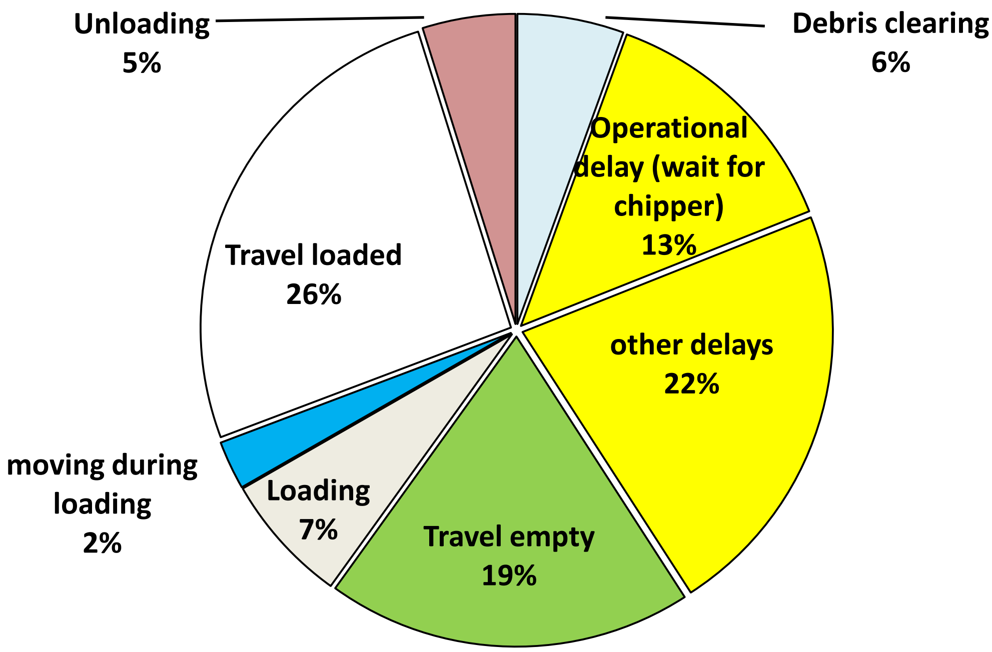

Figure 7: Percentage of work elements and delays for grapple skidder

Productive chipping time, Figures 6 and 7, included only 55% of total study time for the chipper with the other half of its time split between, relocating chipper (10%), waiting for trucks (10%) & wood (4%), knife changes (11%), mechanical (1%) and personal delays (9%).

Table 4 summarizes the delays of the biomass harvesting operations in the study, which shows there is room for productivity gains by focussing on minimizing these significant delays in all phases of the operation.

Table 4: Delays of biomass operation

Machine	Delay (% of worksite time)
Feller-buncher	21
Skidder	25
Chipper	35
Average	27

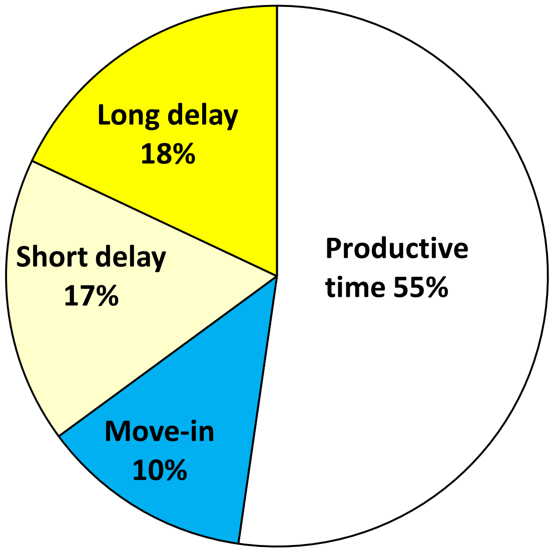

Figure 6: Working time for chipper

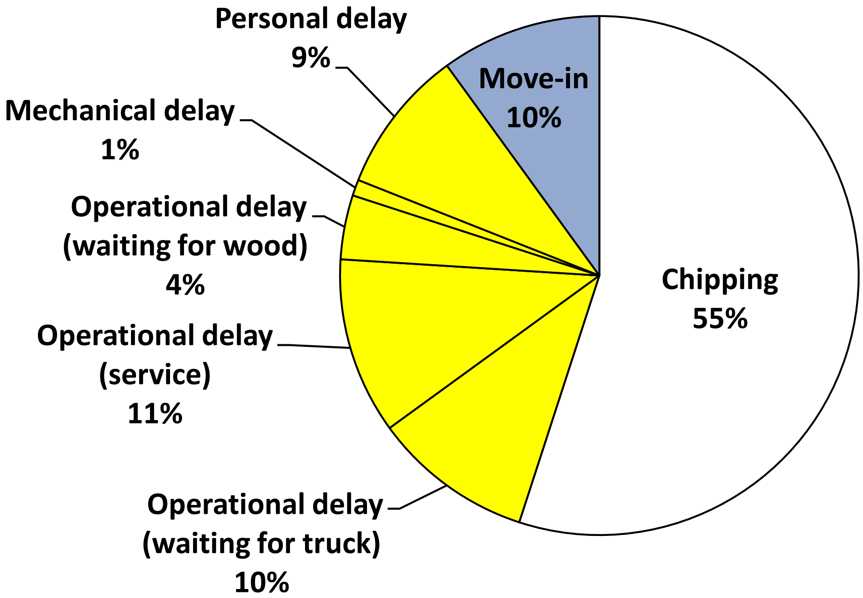

Figure 7: Percentage of work elements and delays for chipper

CONCLUSIONS

Reasonable productions rates can be achieved in very low productive stands when producing energy wood quality chips. Short delays within production time account for around 10% of the study times for each machine studied. Worksite time categorized as long delays for this operation averages over 20%. This significantly affects the utilization rate of the equipment. In-field chipping operations are particularly sensitive to logistics schedules with 10% of the chipper time lost to waiting for trucks.

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INTEGRATING WOODY BIOMASS INTO THE U.S. SOUTH WOOD SUPPLY CHAIN

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ABSTRACT

The rapid growth in announced wood bioenergy plants in the US South has increased the potential annual demand for wood feedstock. Federal legislation creating a renewable electricity standard could significantly increase this projected demand. We examined the potential impacts on the wood supply chain in the US South of this large increased demand. Our research is based on surveys of the forest industry, interviews with biomass harvesting contractors from across the country, and a detailed analysis of data related to the supplies, availability and demand of wood biomass resources in the US South. This allows examination of how new markets could focus on different sources of wood feedstock and how they may compete with existing industry for raw material.

INTRODUCTION

Over the past five years significant interest has developed in replacing fossil energy with renewable energy in the US. This has been driven by higher market prices for petroleum and coal, concerns about impacts of carbon emissions from fossil fuels on climate change, and national security issues associated with importing nearly 70% of US oil from often unfriendly nations. As a result, interest in increasing use of renewable energy, including forest biomass, has grown markedly.

Renewable energy today provides about 7% of total US energy use and roughly half of that is biomass, 75% of which comes from forests. Today most forest biomass is burned to provide process heat and/or steam and in some cases to produce electricity for the forest products industry and the grid. Wood pellet markets have also increased significantly with the primary destination for these products being coal-fired electric plants in the European Union. In addition, most major US electric utilities and several independent electricity producers have announced plans to use wood to produce electricity from new wood-fired plants, co-firing coal with wood, or converting older coal plants to wood feedstock. There is also an infant wood to liquid fuels industry with a handful of plants announced in the US. Collectively, these announcements and plants under construction in the US would consume over 123 million green tons per year by 2020 if successful, with half of this new capacity targeted for the US South (Forisk 2010).

Biomass feedstocks from forests are available in the form of logging residues, currently unmerchantable small stems, understory plants, and wood fiber currently used for other products (e.g., pulpwood). A globally competitive wood supply system is already in place producing traditional roundwood products such as pulpwood and sawtimber as well as clean pulp chips. Markets are developing for other products (wood pellets, electricity from wood, liquid fuels) that can use tree biomass not used by traditional markets. To harvest this additional biomass, we must modify our forest management regimes and forest harvesting systems to obtain the material productively and economically with minimal impacts to the harvested site. Cost-effective harvesting and transportation are the keys to delivering biomass feedstocks at a competitive market price (Aguilar and Garrett 2009). DOE recently identified $47 per dry ton (~$23.50 per green ton) as a target delivered feedstock price for 2012 to make biomass-based processes competitive (Wilkerson et al. 2008). Of this, they target $10/dry ton for the landowner ($5/green ton), leaving $37 per dry ton ($18.50/green ton) available for collection and transportation. These targets have recently been revised, but they represent ambitious goals given the scale of projected biomass demand. They also raise serious questions about the ability of traditional wood using industry to continue to source their facilities at a competitive cost.

We recently examined how the integration of biomass harvesting on a large-scale within a decade would impact the wood supply system in the US, including landowners, logging contractors, and wood using industries (pulp & paper, lumber, panels, and energy). This evaluation included how modifications of today’s harvesting systems could increase the recovery of forest biomass and at what delivered or on-board cost per ton. We evaluated the potential supply of forest biomass from each major forested region of the country given the expected cost of harvesting, collecting, and delivering forest biomass. This analysis also examined likely responses of forest landowner base to price and demand signals in the marketplace prompted by the entry of bioenergy facilities and potential price increases associated with higher demand for biomass and pulpwood products. In this paper, we summarize the expected impacts of greater use of wood for bioenergy on the US South where the bulk of the America’s pulp and paper and forest products industry is today concentrated.

BIOMASS HARVESTING TECHNOLOGY

Our assessment of wood biomass harvesting included a nationally-distributed survey of forest industry professionals and a series of in-depth regional site visits to biomass harvesting contractors. We divided the country into the five regions defined by the Forest Resources Association (FRA) and Wood Supply Research Institute (WSRI) using the approach of the USDA Forest Service Forest Inventory and Analysis (FIA) units (Figure 1). This assessment first examined the rapidly expanding published literature on ways to modify our current harvesting systems to include harvest of traditionally unmerchantable biomass components. We searched both refereed, scientific journals as well as industry trade publications to find contractors and approaches that succeeded in each of the FRA regions. Using the review of literature and through contacts of industry foresters and logging contractors, we compiled a list of top biomass harvesting contractors in each region.

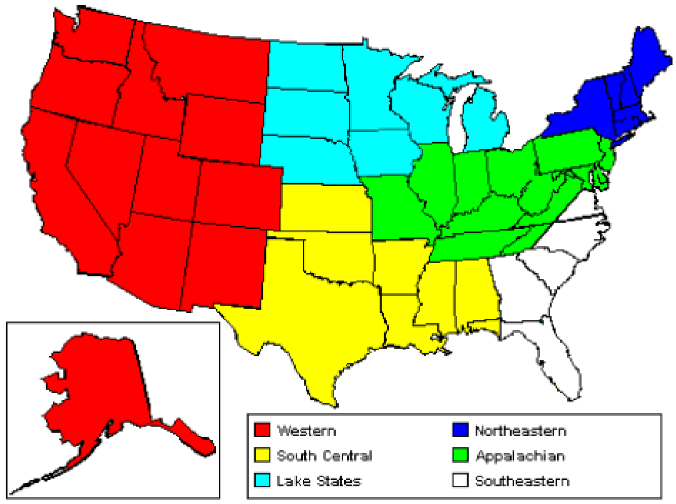

Figure 1: FRA Regions used in study.

Based on our literature review, we developed a short web-based survey that we distributed to each WSRI member company or association and logging associations across the country. Data collected during the survey allowed harvesting contractors to include contact information if they were willing to host an on-site visit. These contacts were combined with lists of high profile biomass contractors gathered from our literature search. We contacted the list of top performers to arrange on-site visits to as many high priority operations as possible during one-week trips to each region during May – August of 2010. Each trip involved at least two members of our forest operations research team. A standard interview form was used to collect common data from each of the operations visited. Information on harvesting system configuration and production were gathered as well as information on resource availability and market strength.

Findings from our web survey of biomass users has been reported by Enrich et al. (2010) and by Greene et al. (2010) and will not be directly summarized here. Instead we report on the findings of our field visits in the US South with comparisons to technology observed in use in other regions where appropriate.

- Pulp mills remain the major market for woody biomass in the South with 90% of those contacted delivering wood fuel to these facilities.
- Biomass is typically purchased on a green ton basis which creates disincentives for allowing feedstocks to dry in the field before delivery for both logging contractors and forest landowners.
- The size of residue material used for woody biomass markets appears to be directly related to the demand and competition for pulpwood by pulp mills in a region. South

Central and Southeast biomass residue markets are harvesting stems less than 4 inches with a significant portion of the material from tree crowns. This is in sharp contrast to other regions of the US where biomass residue material is larger in average diameter and at times may be interchangeable with pulpwood.

- Most operations chip or grind biomass in the field prior to transportation to improve product quality and maximize truck payloads. Grinders are becoming somewhat less common while chippers appear to be expanding in use in the South. Green basis payment encourages the use of chippers which are better with green material, while dry material is best handled by grinders. Reliance on tree-length systems using skidders with residues piled at roadside for grinders appears to introduce more soil contaminants into the residues than use of cut to length systems in other regions. This could be mitigated by piling material with loaders or fork attachments rather than pushing residues with solid blades on skidders.
- Transportation efficiency is critical to the success of biomass harvesting operations and maximizing truck payloads is a key. This is a particular challenge in the South where most state weight laws limit vehicle gross vehicle weight to 40 tons (often with 5-10% allowances) and the use of drop-belly trailers for in-woods use is rare due to the prevalent road building standards.

BIOMASS RESOURCE AVAILABILITY ASSESSMENT

The resource availability research focused on aggregating and analyzing data related to the supplies, availability, and demand of wood biomass resources in the United States. Specifically, this analysis included:

- Confirmation of wood basket regions and relevant raw material types.
- Product specifications for the following harvest types: pre-commercial, thinning and final harvest.
- Analysis of current and historic supply and demand for softwood and hardwood raw materials.
- Detail on current mills and competition for available pulpwood-sized material and woody biomass.
- Based on the estimated forest impacts, assessment of potential impacts on woody biomass supplies.

This research relied on cross-disciplinary data and analysis from public and private sources including the US Forest Service, Forisk Consulting, the Forest Resources Association, and research and guidance from the University of Georgia. In cases where data, analysis, or models from one US forest region were applied to another, all efforts were made to specify the relevant assumptions and potential implications from generalizing results in any way.

Supply Results

Analysis of current wood supplies, as measured by removals (harvested materials), provides a baseline for establishing (1) the magnitude of relevant wood volumes flowing through the system and (2) which of the relevant categories may be more volatile or unreliable as long-term sources of woody biomass. Table 1 includes total current wood removals across five pulpwood and residual categories across the five US regions. We highlight the following from the data:

- The US South is the dominant producer of pulpwood. This finding is wholly consistent with historic research generated by the Forest Resources Association (2005).
- Harvesting activities generate over two times more volume of non-growing stock logging residuals than growing stocking residuals. This is consistent with practice, as harvesting activities generate greater volumes of limbs and tops than cut-offs.
- Mill residues, which flow primarily from primary grade-consuming forest industry facilities, represent a significant volume of raw material for pulp facilities, on-site energy generation and other miscellaneous uses such as animal bedding.

Table 1: Current removals (total green tons), total species, total ownership, 2006.

Region	Pulpwood *	Other Removals	Logging Residues (GS)	Logging Residues (NGS)	Mill Residues (All)
Appalachian	21,075,400	10,589,520	7,288,000	18,936,000	22,630,000
Lake States	33,352,000	11,222,720	2,636,520	14,350,000	14,949,240
Northeast	24,429,880	405,560	2,900,720	13,895,960	6,246,880
South	152,549,200	44,332,120	31,007,400	58,086,560	117,726,080
West	23,352,240	0	6,569,840	27,103,280	66,561,160
Total	*254,758,720*	*66,549,920*	*50,402,480*	*132,371,800*	*228,113,360*

**Includes pulpwood, composite, and fuelwood*

Table 2 details the total, estimated volume by type and region of wood biomass that would be available on an annual basis for consumption by alternative wood users such as bioenergy facilities. The key categories are the two logging residue volumes, growing stock (GS) and non-growing stock (NGS), which together represent 65.6% of the total estimated volume of available materials. The table includes the following assumptions for each type of material:

- Other removals: 50% of total estimated volumes are available.
- Logging residues (GS and NGS): 65% of total estimated volumes are available.
- Mill residues: only unused volumes, as estimated by the US Forest Service TPO data, are available.
- Pre-merchantable materials: following the methods of Conner et al. (2009), 75% of the 1 to 4” dbh class volume on 1/10th of the overstocked acres is available. (This translates to approximately 7.5% of the volume in this specific age class.)

Overall, the South leads all regions with over 90 million green tons of estimated biomass, which represents 50% of all estimated materials nationwide.

Table 2: Current available volume of non-traditional materials.

Region	Other Removals	Logging Residues (GS)	Logging Residues (NGS)	Mill Residues	Pre-merchantable	Total
Appalachian	5,294,760	4,737,200	12,308,400	1,758,560	2,660,988	26,759,908
Lake States	5,611,360	1,713,738	9,327,500	298,000	4,680,492	21,631,090
Northeast	202,780	1,885,468	9,032,374	214,400	5,247,540	16,582,562
South	22,166,060	20,154,810	37,756,264	599,760	9,661,266	90,338,160
West	0	4,270,396	17,617,132	527,960	3,332,083	25,747,571
Total	*33,274,960*	*32,761,612*	*86,041,670*	*3,398,680*	*25,582,368*	*181,059,290*

The composition of biomass materials vary. Overall, two-thirds of the respondents to the UGA biomass user survey noted that at least some portion of the biomass supplied derives from non-merchantable tree species. The balance is primarily a mix of out-of-spec materials, cut-offs, and limbs and tops (Table 3). These results are largely driven by responses from loggers in the US South, the US West and the Lake States.

Table 3: Excluding conventional materials, what is used as biomass (check all that apply)?

	Appalachian	Lake States	Northeast	South Central	Southeast	West	*Total*
Cutoffs	0%	18%	0%	0%	4%	20%	*6%*
Limbs and tops	0%	9%	0%	5%	2%	13%	*5%*
Nonmerch species	100%	45%	75%	66%	77%	47%	*66%*
Out-of-Spec material	0%	18%	0%	21%	13%	7%	*15%*
Premerch material	0%	0%	0%	8%	2%	7%	*4%*
Bark/Fines/Overs	0%	9%	0%	0%	2%	7%	*3%*
Dead wood	0%	0%	25%	0%	0%	0%	*1%*
# Responses	*1*	*11*	*4*	*38*	*47*	*15*	*116*

In practice, the economics and costs of logging operations dictate the feasibility of allocating time and equipment to aggregating and processing wood biomass. Survey results from 53 forestry professionals including loggers, wood dealers, forest managers, and procurement foresters across the US responded that the minimum necessary volume of wood biomass required on a per acre basis to justify recovery ranged from 15 to 25 green tons per acre with minimum total volumes of 250 to 500 green tons and higher (Table 4). Southern operators were looking for at least 15 tons per acre for chipper crews and at least 350 tons on the site for chipper or grinder crews to be feasible. However, the supply data suggested that typical amounts remaining were on the order of 7-8 tons per acre of logging residues with another 10 tons of pre-commercial material that could be added to this (Table 5). This suggests that logging residues as a source of biomass is a marginal opportunity in the South, likely as a result of high wood utilization driven by historically competitive pulpwood markets.

Table 4: Minimum necessary volume that justifies recovery.

	Median (sample size in parantheses)					
	Appalachian	Lake States	Northeastern	South Central	Southeastern	Western
Biomass per Acre	25 (1)	15 (3)	15 (3)	15 (21)	20 (21)	25 (4)
Biomass per Site	250 (1)	480 (4)	n/a	350 (21)	500 (26)	550 (4)

Table 5: South available supplies per acre.

Harvest Type	Biomass Supply (Non-merch) in green tons per acre			
	Logging residue		Pre-merch	Total
	Slash, limbs, tops	Cut-offs and Out-of-spec		
Pre-commercial	0	0	10	10
Thinning	5	3	0	7
Final Harvest	5	3	0	7

Wood Demand Results

Analysis of pulpwood demand by US region since 2005 highlights two findings (Table 6):

- Most pulpwood, hardwood and softwood, is consumed in the US South.
- Pulpwood consumption, nation-wide, has remained relatively static, declining 4% (or 0.9% annually), between 2005 and 2009. The drivers behind this are (1) pulp markets declined less in the economic downturn than did lumber and building products and (2) pulp mills purchased additional volumes of pulpwood roundwood as a percentage of their total raw material consumption to offset decreases in residual chip production from sawmills.

Table 6: Pulpwood and chip demand by region, green tons, hardwood and softwood*

Market	2005	2006	2007	2008	2009	% change 05-09
Appalachian	13,609,122	14,356,732	14,612,528	14,398,514	13,456,867	-1%
Lake States	21,307,377	22,428,337	22,150,448	21,809,114	20,505,674	-4%
Northeast	12,668,714	13,277,815	13,521,970	13,284,641	12,352,791	-2%
South	172,890,369	185,123,690	189,312,002	183,259,000	165,600,752	-4%
West	24,087,152	25,520,406	26,010,797	25,459,840	23,513,924	-2%
Total	*244,562,734*	*260,706,979*	*265,607,745*	*258,211,110*	*235,430,008*	-4%

Source: Forisk Consulting, Forest Resources Association (FRA)
**Includes in-woods and mill residue chip receipts. According to FRA, residue chips made up 29% of total pulpwood receipts in Northeast in 2004, 19% of receipts in Lake States in 2004, 25% of receipts in the South, and 66% of receipts in the West in 2004.*

Grade (sawtimber and plywood) consumption has also declined over the past five years. Taken together, total wood demand of grade and pulpwood products declined by 23% for the entire US (Table 7). The largest percentage declines were in the West (39%) and the South (19%).

Table 7: Total hardwood and softwood demand (all products), 2005-2009, green tons.

Market	2005	2006	2007	2008	2009	% change 05-09
Appalachian	33,173,922	33,599,732	33,000,888	31,071,234	29,469,572	-11%
Lake States	29,680,797	30,910,214	29,988,786	26,881,469	25,349,818	-15%
Northeast	22,538,554	23,485,055	23,712,610	21,891,961	20,119,415	-11%
South	308,933,549	308,838,908	308,498,297	285,953,743	250,317,268	-19%
West	127,576,692	120,366,731	115,007,289	94,819,628	77,812,833	-39%
Total	*521,903,514*	*517,200,640*	*510,207,870*	*460,618,036*	*403,068,906*	-23%

Wood Bioenergy Results

In 2008, Forisk began tracking bioenergy projects in the US using a bioenergy screening methodology that relies on two criteria for wood-consuming projects (Mendell and Lang 2010):

- Technology: projects that employ currently viable technology pass the technology screen. These include pelletizing technology and wood-to-electricity projects. Cellulosic ethanol from wood feedstock is still a developing technology and is currently not operational.
- Status: projects that are operational, under construction, or have received or secured two or more necessary elements for advancing towards operations pass the status screen.

We applied the screening methodology to all 432 known operating and announced wood-using bioenergy facilities in Forisk's *Wood Bioenergy US* database as of November 10, 2010 (Table 18). This does not include all cogeneration plants operating at pulp and paper facilities. By count, electricity and pellet projects comprise 91% of all projects, with cellulosic ethanol-oriented liquid fuel projects representing most of the balance. Regionally, the US South has the largest number of projects in total and by technology type, the highest potential wood use from operating and announced projects, and the highest volume of wood associated with projects that pass the basic viability screening.

Table 8: Announced and operating wood bioenergy project count.

	Type				
Region	**Electricity**	**Liquid Fuel**	**Pellet**	**Total**	***Total that pass screens***
Appalachian	24	6	37	67	48
Lake States	17	4	25	46	35
Northeast	55	4	27	86	58
South	81	17	45	143	79
West	55	7	28	90	57
Total	232	38	162	432	277

The screen was applied individually to all operating and announced wood bioenergy projects in each US region. As of November 2010, the projects accounted for in Table 8 represent potential, incremental wood use of 123 million green tons per year by 2020.[1] Projects representing 68.4 million tons per year passed the basic screening described for the entire US. This represents less than 56% of the potential, announced wood demand from bioenergy projects and provides an indication of how much actual, incremental wood demand we might expect given what's known today about these projects.

The US South region includes 143 announced and operating wood bioenergy projects, of which 79 pass the viability screens (55.2% pass rate). Table 9 summarizes the estimated wood consumption by year for these projects through 2020. These projects represent potential, incremental wood use of 59.2 million greens tons per year by 2020, of which 25.2 million (42.6%) pass basic screening.

Table 9: Wood demand from bioenergy in South region, all feedstocks, million green tons/year.

South	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
All Electricity	3.71	4.87	8.18	17.10	28.07	29.93	32.85	33.91	33.96	35.02	35.08	35.14
All Liquid Fuels	0.50	0.61	1.15	1.35	4.05	4.38	5.98	9.70	9.70	10.51	10.51	10.51
All Pellet	4.03	5.84	10.20	13.11	13.57	13.57	13.57	13.57	13.57	13.57	13.57	13.57
Total	**8.24**	**11.31**	**19.53**	**31.56**	**45.69**	**47.87**	**52.39**	**57.18**	**57.23**	**59.10**	**59.16**	**59.21**
Total that pass screens	**7.74**	**9.75**	**15.79**	**22.03**	**24.08**	**24.58**	**24.88**	**24.93**	**24.99**	**25.05**	**25.11**	**25.17**

Table 10 and Figure 2 summarize the sustainability results for the South. Non-traditional material supplies of 90.3 million tons per year exceed projected bioenergy demand through 2020. Industry demand for pulpwood can be satisfied with growth and does not impact the pulpwood stock's ability to grow. Net growth increases each year through 2020. If we remove the other removals category from the non-traditional material supply the total annual supply drops to 68.2 million tons per year. Logging residues, mill residues, and pre-merchantable material satisfy bioenergy demand until 2020. If we remove pre-merchantable materials from the non-traditional supply, the non-traditional supply drops to 58.5 million tons per year. At the reduced level of logging residues and mill residues alone, non-traditional materials can satisfy bioenergy demand until 2018. By 2020 the surplus bioenergy demand exceeds 700,000 tons per year excluding other removals and pre-merchantable material.

[1] These estimates focus on "green" tons, which measures wood raw material as it leaves the forest with moisture content of 40-50%. Specifically, green tons refer to 2,000 pounds of undried biomass material. Since bioenergy facilities consume raw material on a "dry" ton basis, moisture content must be specified if green tons are used as a measure of fuel energy. The "rule of thumb" applied in this study is a 2:1 ratio of green to dry tons (two tons of green wood equates to one ton of dry wood raw material).

Table 10: Sustainability results for US South pulpwood supplies.

Category	2009	2010	2015	2020
Growing stock*	2,852,450,299	2,897,541,193	3,182,149,395	3,597,817,132
Growth	224,481,479	228,030,032	250,428,063	283,140,187
"Non-traditional" materials***	90,338,160	90,338,160	90,338,160	90,338,160
Demand: Industry**	179,390,585	179,390,585	179,390,585	179,390,585
Demand: Bioenergy total	8,241,500	11,314,170	52,391,776	59,214,102
Bio demand not met by non-trad	0	0	0	0
Implied Net Growth	45,090,894	48,639,447	71,037,478	103,749,602
Annual % Growth	7.87%	7.87%	7.87%	7.87%

**Assume current merchantable inventory number as base*
*** Average 2007-2009*
****Assume same as 2006 or current estimate*

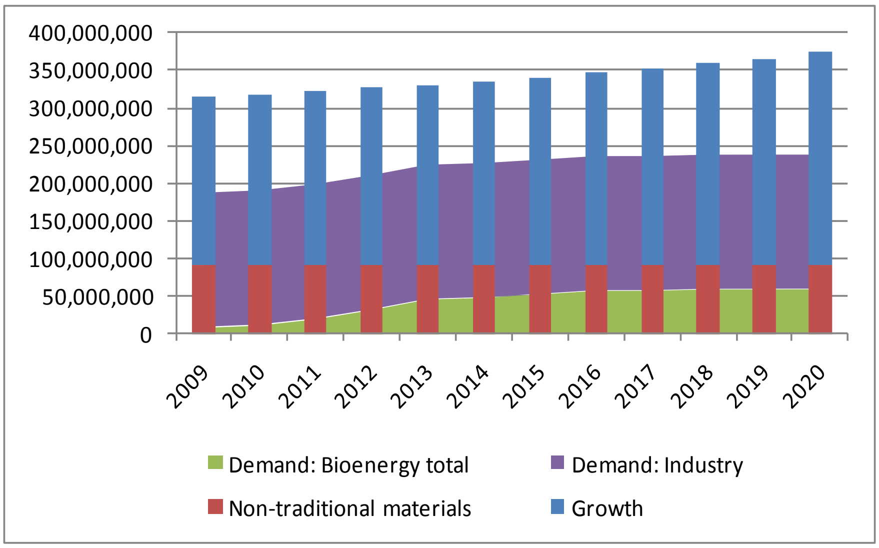

Figure 2: Pulpwood growth and sustainability in the South

SUMMARY

- <u>Biomass supplies:</u> US forests and mills generate ~181 million available green tons of non-traditional, unused woody biomass. These include "other" removals, logging residues, unused mill residues and pre-merchantable materials. The key categories are two types of logging residues, which together represent 65.6% of these materials. Overall, the South accounts for 90 million green tons, or 49.9% of all estimated materials nation-wide.
- <u>US forest harvesting:</u> The US harvests 2.1% of its timberlands annually. Nationally, this has been relatively stable for the past 20 years. Regionally, harvesting has increased in the South and Northeast and decreased in the West and Lake States. Approximately 60% of all harvesting activities today are partial cuts or thinnings. For biomass harvests

associated with standard logging operations, operational viability requires 15 to 25 tons per acre minimum, while most available biomass volumes across US regions fall below 15 tons per acre on average. Alternately, grinder operations that follow logging operations require minimum volumes per site, rather than per acre volumes, that range from 250 tons to 550 tons per site.

- Wood demand: In 2009, the US forest products industry consumed 235.4 million tons of pulpwood and chips, 4% less than in 2005. The South accounts for 70% of this demand.
- Wood bioenergy projects: Of the 143 announced and operating wood bioenergy projects in the US South, 79 pass basic viability screening. These "viable" projects represent 25.2 million tons of incremental wood biomass demand by 2020.
- Sustainability: Two sets of sustainability metrics indicate that, on both national and regional bases, the US South grows more than enough wood biomass from traditional sources to supply both known wood bioenergy projects that are likely to succeed and the current forest industry. While heartening for long-term planning, this same assessment tells us nothing regarding the operational, economic and political viability of sustainably supplying wood raw materials for a given wood bioenergy project in a given local wood basket.

ACKNOWLEDGEMENTS

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ESTIMATING FOREST ROAD AGGREGATE STRENGTH BY MEASURING FUNDAMENTAL AGGREGATE PROPERTIES

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ABSTRACT

The depth of aggregate required for forest road pavements is dependent on the characteristics of the expected traffic, and the subgrade and aggregate layer bearing strengths. The first two factors are relatively easy to estimate; however, determining aggregate bearing strength is an arduous and expensive task. Forest road engineers typically forgo aggregate testing when using locally sourced material and assume that the aggregate has appropriate strength. This assumption is often erroneous and can lead to pavement depths that are either insufficient or excessive. The risk of over- or under-engineering could be reduced if engineers were able to easily quantify the strength of locally sourced aggregates. The goal of this study is to develop a simple, low-cost method to estimate bearing strength by correlation to fundamental aggregate properties.

Forest road aggregates were collected and tested to determine their fundamental properties and bearing strength. The properties measured for each aggregate included Broken Face Content, Micro-Deval Test value, Plasticity Index, Slenderness Ratio and Solid Density. Bearing strength was determined using the California Bearing Ratio test, with samples prepared at optimum moisture content using standard compaction effort and the Driving Surface Aggregate gradation.

Multiple linear regression analysis of the results shows that aggregate strength decreases when the Slenderness Ratio, Broken Face Content and Micro-Deval Test values increase. The regression is sufficiently robust to enable the approximate bearing capacity of an aggregate to be estimated as poor, fair or good. The quality of this regression may be improved by the addition of further aggregate samples.

Keywords: Aggregate, CBR, forest road, unsealed road

INTRODUCTION

Forest roads in New Zealand are typically constructed using a single layer of unbound aggregate spread over a prepared subgrade. The purpose of the aggregate layer is to provide a high strength material that elastically deforms under truck tyres to disperse, and thus reduce, applied stresses to a level that can be borne by the underlying subgrade. Stress dispersion increases as the thickness and strength of the aggregate layer increases. This aggregate layer is often the most expensive component of forest road construction, contributing up to 60-70% of the total construction cost. The consequence is that forest road engineers need to optimise the trade-off between pavement thickness and cost to produce forest roads that are both affordable and fit for purpose.

The thickness of aggregate used for a forest road pavement is dependent on a number of factors, including the expected traffic characteristics, and the subgrade and aggregate layer strengths. These first two factors are relatively easy to estimate or measure; however, determining aggregate strength is a more arduous and expensive task. Consequently, many forest road engineers forgo aggregate testing when using locally sourced material and assume that the aggregate has appropriate strength for the task. This assumption is often erroneous and can lead to designed pavement depths that are either insufficient or excessive. In the former case, pavements can prematurely fail with costly rehabilitation and serious disruptions to log hauling operations. In the latter case, the road may easily meet the required level of service but will be unduly expensive to construct. The risk of over- or under-engineering the unbound aggregate layer could be reduced if engineers were able to easily quantify the bearing strength potential of locally sourced aggregate materials and adjust the pavement thickness accordingly. The goal of this study is to develop a simple and low-cost method that estimates bearing strength by correlation to easily measured aggregate properties.

LITERATURE REVIEW

Research on the durability of aggregates is well advanced, with numerous tests developed to identify materials that are prone to deterioration and are unsuitable for road construction (Paige-Green 2007). Aggregate standards use these tests to identify whether an aggregate meets minimum specifications, for example, the TNZ M/4 Specification for Basecourse Aggregate (TransitNZ 2006) requires aggregates to meet or exceed specifications for crush and abrasion resistance, chemical weathering, CBR value, plasticity index, broken face content and particle size distribution. Little guidance is provide for the use of aggregates that fail to meet these standards, though use of non-compliant aggregates is commonplace for construction of forest roads and many low-volume public roads.

Research predicting Californian Bearing Ratio (CBR) from fundamental properties has to date primarily focussed on subgrade soils (Black 1962, Agarwal and Ghanekar 1970, NCHRP 2001, Taskiran 2010). Similar research for the aggregate layer is limited. Kamal *et al* (2006) developed a Toughness Index for aggregates based on results from aggregate laboratory tests; however, this index was designed to assess relative quality of roading materials, rather than a quantitative measure of bearing strength. A study by the Colorado Department of Transport (2003) showed that the Micro-Deval Test (MDT) value was a good indicator of aggregate quality. The resulting MDT value was able to rank aggregates as poor, fair or good; but again did not provided a quantitative measure of aggregate strength that could be used in aggregate thickness design algorithms.

Other aggregate research has investigated the behaviour of the aggregate layer under load. Theyse (2002) researched the performance of unbound granular aggregate in South Africa, with specific focus on predicting permanent deformation of the aggregate layer. Theyse concluded that the most influential factors were the dry density of the aggregate, moisture content and a ratio that combined effects of confinement and stress. A study by Barksdale (1989) examined unbound aggregate performance in relation to rutting. The study examined how the size and shape of coarse aggregate particles influenced performance under load. Barksdale concluded that although smooth rounded rocks rutted more readily, they performed similarly to, if not better than, angular rocks in relation to permanent deformation under stress.

Aggregate properties that are understood to significantly affect layer strength are gradation (Arnold *et al* 2007) and compaction. Numerous aggregate grading curves have been developed for use on forest roads (Fairbrother *et al* 2009); with the Driving Surface Aggregate design being an indicator of best-practice for forest roads (Fairbrother 2011). It is also widely accepted that variation in moisture content and compaction effort dramatically affect the maximum dry density and strength potential of aggregate layers (Bowles 1992). Consequently, research evaluating aggregate layer strength from fundamental aggregate properties needs to exclude water content, dry density and aggregate gradation as variables.

METHOD

Representative samples of 18 forest road aggregates were collected from the East Coast, Canterbury and Otago regions of New Zealand. The samples were collected from either quarries or in-forest stockpiles and were representative of materials being used at the time for single-layer, forest road pavements. A 15kg test specimen was then prepared from each sample by standardising the aggregate to comply with a best-practice unsealed road aggregate gradation curve. This standardisation was necessary as many aggregate samples were too coarse for effective laboratory testing, but also enabled aggregate gradation to be excluded as a variable. The Driving Surface Aggregate gradation (PSU 2006) used for this research and is illustrated below in Figure 1.

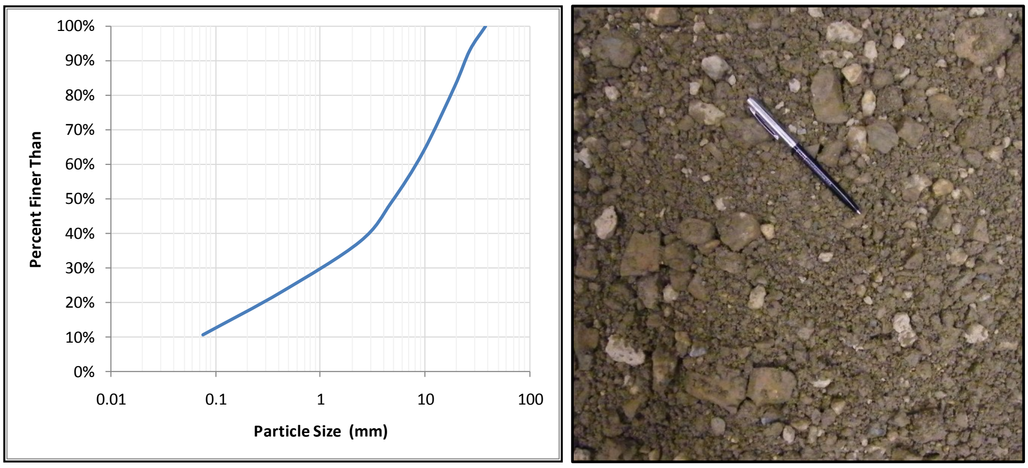

Figure 1: The gradation curve used to prepare each aggregate sample; and a photograph of a DSA graded aggregate sample.

Each aggregate was compacted using a standard compaction effort in accordance with NZS4407 Test 3.15 (Standards NZ 1991) with the specimen prepared at optimum moisture content (OMC) – the moisture content at which maximum dry density can be achieved for a given compaction effort. The OMC for each aggregate was estimated by mixing the specimen with sufficient water so that a hand-compacted ball of material retained its shape. A sample was too dry if the ball crumbled and too wet if it would not compact (PSU 2006). An aggregate sample prepared using this method is show below in Figure 2.

Figure 2: A photograph showing the method used to determine OMC. The samples on the left and right are too dry and too wet respectively. The middle sample has been prepared at OMC.

The bearing strength of the prepared specimens was established using the Californian Bearing Ratio Test, NZS4407 Test 3.15 (Standards NZ 1991). Early testing showed that bearing strength of an aggregate varied widely between tests, most likely due to the random packing of the larger gravel components. Consequently, seven CBR tests were completed for each aggregate in order to establish a median CBR value.

The following fundamental properties of each aggregate were assessed once CBR testing was completed:

- Broken Face Content, NZS4407 Test 3.14, (Standards NZ 1991) – a measure of the percentage of aggregate particles that have at least two broken faces. This test distinguishes between crushed aggregates and rounded 'river run' aggregates.
- Micro-Deval Test, ASTM D6928-06, (ASTM 2006) – a measure of the abrasion resistance and durability of aggregate particles. A lower MDT value indicates a more durable aggregate. An aggregate with MDT>18% is deemed to be poor road construction material (CDOT 2003)
- Plasticity Index, NZS4407 Test 3.4, (Standards NZ 1991) – a measure of the plasticity of the fine material within an aggregate. A plasticity index value between 8 and 12 is appropriate for aggregates used in temperate environments with moderate rainfall (Giummarra, 2009).
- Slenderness Ratio, NZS4407 Test 3.13, (Standards NZ 1991) – indicates whether the aggregate particles are long and slender or short and squat. A lower value indicates a more squat aggregate.
- Solid Density, NZS4407 Test 3.7 (Standards NZ 1991) – the solid density of the aggregate particles in tonnes per cubic metre.

RESULTS

Test results are presented below in Table 1.

Table 1: Aggregate CBR and Fundamental Properties Test Results

Aggregate #	1	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Median CBR (%)	35	44	36	50	41	50	40	48	57	48	48	38	57	69	60	27	28
Slenderness Ratio	2.13	2.45	2.13	2.11	2.20	1.74	2.00	2.22	2.05	2.25	2.65	2.29	1.89	1.90	2.08	2.13	2.52
Plasticity Index	8	8	10	9	10	7	8	9	7	10	8	9	6	0	6	8	8
Broken Faces (%)	100	67	100	60	94	100	100	100	100	98	100	100	42	35	90	100	100
MDT Value (%)	31	28	30	31	26	26	37	11	12	22	16	15	18	22	15	29	34
Solid Density	2.59	2.64	2.55	2.55	2.59	2.50	2.57	2.89	2.78	2.54	2.53	2.60	2.57	2.59	2.62	2.59	2.64

Aggregate #2 has been omitted from the results, as this aggregate had an extreme MDT value of 97.5% that was disproportionately affecting the analysis. This outlier is a consequence of the aggregate being a very weak sandstone that behaved as a fine-grained soil, rather than an aggregate, during the Micro-Deval Test.

ANALYSIS

The results indicate that the median bearing strength of the forest road aggregates varies from a CBR of 27 through to a CBR of 69. This is a significant finding in itself, as the most commonly known unbound granular pavement design methods for light roads in Australia and New Zealand, the APRG 21 method (ARRB 1998) and the AUSTROADS 'Figure 8.4' method (AUSTROADS 1992), both assume that the aggregate will have a minimum CBR bearing strength of 80. None of the tested aggregates meet this standard, while many fall well short. The consequence is that forest roads designed using these methods and constructed with the tested aggregates are likely to be under-engineered and face the prospect of early failure.

Initial exploratory data analysis examined the correlation between single variables and median CBR. This analysis identified that Broken Face Content, Micro-Deval Test Value and Plasticity Index have a moderately strong linear correlation with median CBR. However, the Broken Face Content correlation was over-stated by the limited number of samples comprised of rounded material and the Plasticity Index correlation was significantly over-stated by the single aggregate sample with a plasticity index equal to zero. Slenderness Ratio had a weak correlation, while solid density had no linear correlation. Further aggregate samples are needed to confirm the veracity of theses correlations. Graphs for each variable are presented below as Figure 3.

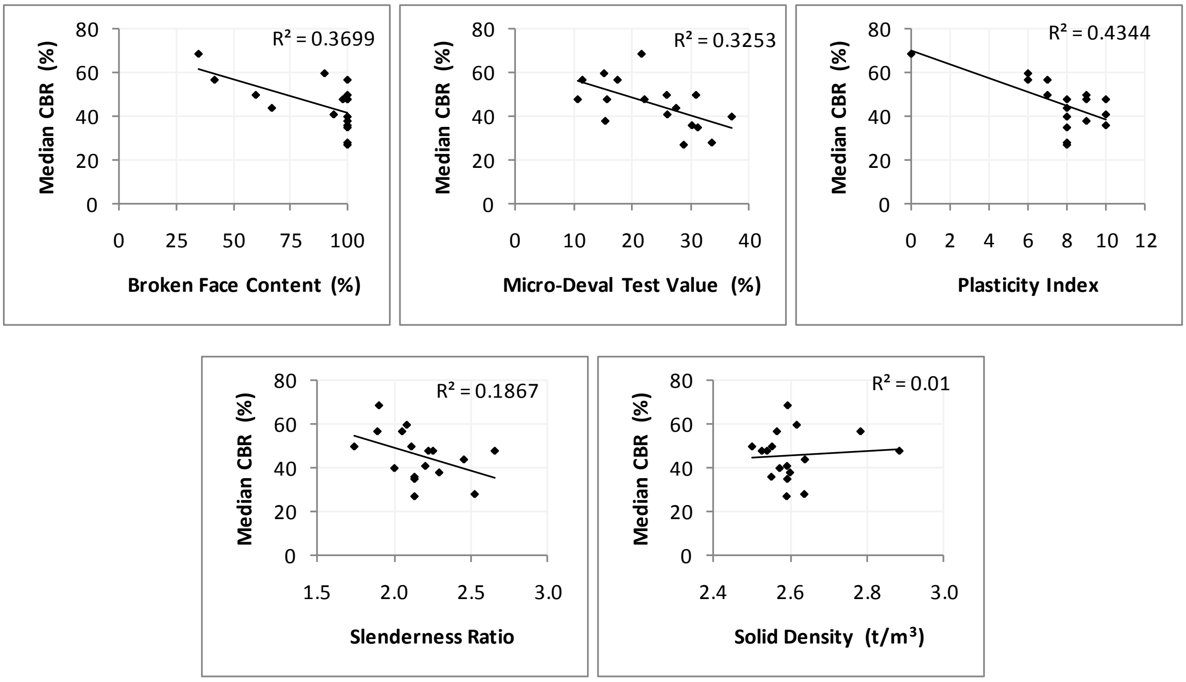

Figure 3: Graphs illustrating the correlation between each of the independent variables and median CBR

The finding that aggregates with rounded rocks have greater bearing strength than those using crushed rocks is consistent with other research (Barksdale 1989) and questions the value of crushing rounded aggregates to improve aggregate strength. Note that this result may be biased, given that the rounded rocks tended to also be squatter and stronger due to the nature of their river-borne transport process. Furthermore, the relative resistance to ravelling of crushed and rounded aggregates on-road is an important property that was not considered by these tests. Further research is required before any conclusions can be drawn on the whether or not to crush rounded aggregates.

The data was further analysed using multiple linear regression to examine whether a combination of fundamental aggregate properties could better predict median CBR. This analysis showed that the best fit was achieved when using Broken Face Content, Micro-Deval Test Value and Slenderness Ratio as the independent variables. The resulting correlation equation is presented below as Equation 1. The adjusted coefficient of determination for this equation is $R_{adj}^2=0.68$. Note that this regression equation is only applicable for aggregates prepared in accordance with the method used for this research.

$$Median\ CBR = 117 - 25.2\ (BF) - 77.9\ (MD) - 14.4\ (SR) \tag{1}$$

BF = Broken Face Content (%), MD = Micro-Deval Test Value (%), SR = Slenderness Ratio

A plot of predicted median CBR versus actual median CBR is presented below as Figure 4. The regression equation is sufficiently robust to enable the approximate bearing capacity of an aggregate to be estimated as poor (CBR<40), fair (40<CBR<60) or good (CBR>60).

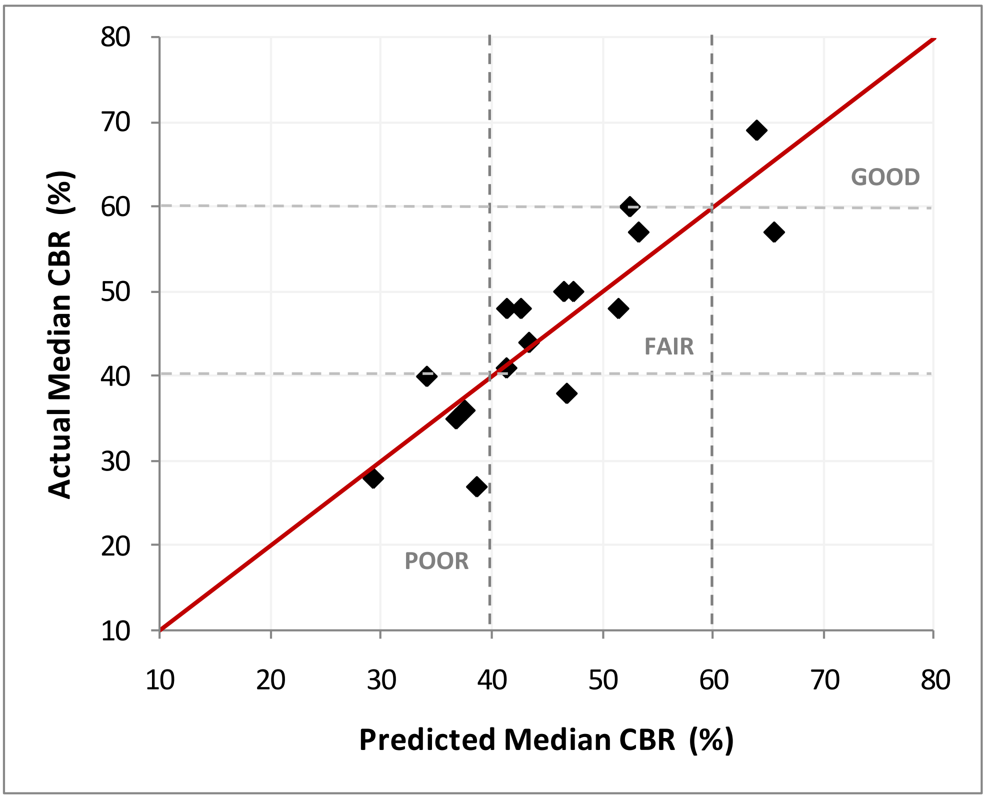

Figure 4: Graph of the correlation between Predicted Median CBR and Actual Median CBR.

CONCLUSION

This research shows that aggregate bearing strength, as measured by CBR, can be estimated from fundamental aggregate properties. Multiple linear regression analysis of the test results shows that aggregate strength decreases when the Slenderness Ratio, Broken Face Content and Micro-Deval Test values increase. Predicting aggregate bearing strength using these three tests is relatively simple, quick and inexpensive when compared to the effort required for repeat CBR testing. The Slenderness Ratio and Broken Face Content tests can be completed using rudimentary laboratory equipment or estimated by the forest road engineer on-site; however, the Micro-Deval Test value is somewhat more difficult to obtain, requiring specialist laboratory equipment.

The regression equation is sufficiently robust to enable the approximate bearing capacity of an aggregate to be estimated as poor (CBR<40), fair (40<CBR<60) or good (CBR>60). This level of precision is sufficient for use in pavement design equations that require the aggregate layer CBR value as an independent variable, such as the aggregate surfaced design method developed for the US Forest Service (Barber et al, 1978). The quality of this regression may be improved by the addition of further aggregate samples.

This research also questions whether rounded aggregates should be crushed, and whether locally sourced forest road aggregates can be used with common pavement thickness design algorithms. Both of these questions warrant further research.

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Intermodal roundwood transport: Pre-carriage optimization ensuring economic and environmental benefits

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Abstract

Due to concentration processes in the European wood based industry and larger capacities in the installed units, the procurement radius has increased significantly over the last decade. Average transport distances today are approximately 150 km (one-way) and are likely to increase in the future. As a consequence transportation activities account for a substantial part of the total raw material costs at mill gate. Given the relatively dense rail and water way network in Central Europe it is claimed that the use of rail or ship for long distance roundwood transport is beneficial regarding both economic and environmental aspects in comparison to truck transport. Nevertheless this can only be realized by intermodal transport solutions as truck transport remains an inevitable component in roundwood transportation due to the remoteness of the constantly changing harvesting sites in the forest from logistic terminals. On the basis of case studies where long distance roundwood transport from the forest to the mill was carried out alternatively with trucks only and with intermodal systems (truck – rail – truck, truck – ship – truck) respectively, the comparison regarding total transport costs as well as energy efficiency and GHG emissions gives a more heterogeneous picture. The inevitable necessity for pre-carriage, detours and often additional onward-carriage risks to outweigh the potential benefits of intermodal transport solutions and requires rigorous observation and minimization of pre-carriage distances independently of the main carrier to ensure these economic and environmental advantages. The results can contribute to optimizing transport solutions and to avoid that opposing effects related to transport put the good ecological reputation of wood at stake.

Keywords: Intermodal transports, roundwood transportation, energy efficiency, economic and environmental assessment, transport optimization;

Introduction

The transport of roundwood from the place of origin (forest) to the point of first conversion (mill) is technically and economically challenging, given the fact, that the sources of origin are naturally much dispersed, constantly change over time and thus remote from logistic terminals and that roundwood is a bulky product with a relatively low weight / volume ratio. Wood transport is carried out with special trucks in most cases, which hampers the organization of back-haulage. The related costs as well as the environmental impacts (emissions, fossil energy consumption) are in conflict with an otherwise positive eco-profile of wood and wood products. Due to these reasons sawmills try to organize their roundwood supply in a way, that transport distances are minimized. In the southern part of Germany, average transport distance of sawmills ranges between 70-150 km (one way distance). Growing mill capacities in the last decade generally lead to increased transport distances. Long distance transport is common already today, if it comes to “unplanned” roundwood supply due to large windthrow events, which became more and more frequent in the last decades. These catastrophic events result in big quantities of (lower priced) roundwood at the market. The surrounding mills are usually only capable to absorb a low percentage of this volume. Thus, in order to absorb these quantities, long distance transport of roundwood is organized, which can range between 300 and 1000 km, depending on the distance from the area affected by the windfall to the respective mill. Here transport by rail or ship is regularly being carried out as it is believed, that above a certain transport distance rail and ship are superior to truck transport regarding both economic and ecological aspects. Due to the remoteness and the constant source location change both rail and ship require pre-carriage from the forest to logistic terminals. Thus, speaking of transport by rail or ship in roundwood transportation needs to be regarded as intermodal transport.

Material

Case study Kyrill

The last big storm event in Germany, named Kyrill, blew down an estimated roundwood volume of about 37 million m^3 on 18th/19th January 2007, nearly 16 million m^3 of which on a cleared area of 30.000 ha in the federal state of North Rhine-Westphalia in the central west of Germany. A big sawmill X in southern Germany purchased a total of 57.000 m^3 from this area. The air-line distance between the windfall area and the sawmill was approximately 400 km.

As sawmill X is situated relatively close to a rail terminal and to a fluvial harbour, they organized the transport in a way, that 43.000 m^3 were transported by ship via channels and rivers and 14.000 m^3 by railway. All relevant data for these transports were recorded in detail.

Another sawmill Y in southern Germany, located far away from any river and railway line, had also purchased roundwood from the same windfall area, and organized their transport totally by trucks. Also for this transport alternative, the relevant figures were recorded as real data.

Methods

These two data sets allowed a comparative analysis. For sawmill X the (real) data for ship and railway transport were compared to a virtual truck transport of sawmill X, modelled with real data of sawmill Y.

The first objective was to analyse and compare both economic and environmental parameters for an alternative rail/ship/truck transport from the windfall area to mill X. In a second step the inevitable trucking part within intermodal transport has been minimized to analyse the effect on the overall performance of the different transport solutions and the choice of the main carrier.

The following criteria were selected: transport distances for the different means of transportation, total transport costs at mill gate, energy consumption and the related total CO_2 and NO_X emissions for the alternative chains. The reference unit was one m^3 roundwood. Included into the system boundaries were all transport costs and the direct energy consumption and emissions related to the means of transportation. For all truck transport phases empty back-haulage was included whereas rail and ship transport were calculated for the one-way distances. Also the energy consumption and emissions of the pre-chains to produce diesel for trucks, ships and railway and electricity for railway were included. Not included were material and energy input for construction and maintenance of the transport means as well as the energy input, emissions and costs for traffic infrastructure (building, maintenance and management of roads, railway lines, rivers and fluvial channels).

Volumes and tonnage of the transported roundwood, conversion factors from volume to weight of roundwood, distances, costs and fuel consumption of the trucks were directly collected at mill X and Y respectively. Standard data from environmental data bases (EcoTransIT, HBEFA) were used to calculate the energy consumption of ship and railway and the emissions of CO_2 and NO_X related to all three means of transportation. Also for the conversion between the different forms of energy standard conversion factors were used. To provide a comprehensive and comparable analysis of all three process chains, the three alternatives were modelled using the event driven process chain concept (EPC).
For the transport optimization the volumes were assigned to the nearest terminal independent of its nature as port or rail terminal.

Results
The transport distances showed no big differences between direct truck transport and ship but shorter distances for rail transport. This was due to the empty back-haulage on the one hand and fairly high detour factors for ship transport including longer pre-carriage distances compared to the rail transport.
The results of the cost analysis show that under the given circumstances, the costs of direct truck transport and of transport by ship are nearly equivalent. The cheaper main transport phase by ship is partly outweighed by long and expensive pre-carriage to the harbour. Transport by rail was cheaper, which was mainly due to the fact that the pre-carriage distance and cost, from the forest to the rail station, was lower.
Regarding the specific energy consumption, rail and ship are by far more energy efficient than truck transport.
The CO_2 emissions follow the pattern of primary energy consumption. Truck transport nearly has double CO_2 emissions compared to rail and ship.
The relative high CO_2 emissions from railway transport is due to the fact, that the electricity mix for railway transport includes a substantial part of electricity produced by brown coal. In other countries or regions, where the electricity is produced primarily with e.g. hydro power, the railway may benefit from this fact. An additional reason is the dependence on diesel engines on the secondary lines of the rail network that are characteristic to rail roundwood transportation
The picture is different regarding the NO_X emissions. Ship and truck are both fuelled by diesel and therefore have a clear disadvantage compared to rail with the largest share being electric traction.

Conclusions
The results show clearly, that the cost advantages and environmental benefits of ship and rail transport phases, are partly outweighed by the necessity of pre-carriage - the roundwood has to be transported from the forest to the nearest port / rail terminal by truck - and that even big mills do not always have direct access to fluvial / railway lines, which makes onward-carriage necessary - again by truck. Loading between the different carriers also causes higher lead times and additional costs.
Pre-carriage constituted a substantial expense factor but is inevitable in intermodal roundwood transport. Minimizing this by assigning the volume of each pile to the nearest terminal independent of the main carrier, a strong shift towards more rail transport could be observed. This is only practical if the terminals capability is high enough.
A consequence would be, that the (dense) railway network in Central Europe, and especially in Germany should provide more stations which technically allow the loading of roundwood on the railway. Sawmills and other wood industries should be connected directly to railway and/or should have close fluvial access to be able to make full use of the cost benefits and the

environmental advantage of long distance transport by alternative transport means (ship and railway).

In the case study, bottlenecks at the loading stations (railway loading stations and harbours) were quite common during the hot phase of the windfall logging campaign. Consequently the pre-transport distance was not always optimal. An alternative calculation using the optimal distances from the respective forest location to the next harbour / railway station resulted in a substantial decrease of the pre-chain distances. This shows that a very careful logistic planning of the wood flow can contribute to lower transport distances and the related cost and environmental impacts especially in the case of catastrophic events.

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