Welcome to the Council on Forest Engineering(COFE)

Publications Website

Engineering New Solutions for Energy Supply and Demand

September 9-12, 2012, New Bern, North Carolina

Select an individual paper from the list below. Papers are listed in alphabetical order by first author.

- Baker, Shawn A. and W. Dale Greene. Logging Cost Components in the US South
- Beaudoin, Daniel and Luc LeBel. A FRP model to improve wood yard operations from log deliveries to sawmilling outputs
- Beck, Storm and John Sessions. Ant Colony Optimization for Road Modifications
- Benjamin, Jeffrey G., Emily Meacham, Robert Seymour and Jeremy Wilson. Early Commercial Thinning in Maine's Spruce-Fir Forests
- Chung, Woodam and Nathaniel Anderson. Spatial modeling of potential woody biomass flow
- Chung, Woodam, Dongyeob Kim and Nathaniel Anderson. Productivity and cost analysis of a mobile pyrolysis system deployed to convert mill residues into biochar
- Coltrin, William R., Sang-Kyun Han and Han-Sup Han. Costs and Productivities of Forest Biomass Harvesting Operations: A Literature Synthesis
- Conrad IV, Joseph L. and M. Chad Bolding. Harvesting Productivity and Costs When Utilizing Energywood from Pine Plantations of the Southern Coastal Plain, USA
- Cutshall, Jason B., Shawn A. Baker and W. Dale Greene. Improving Woody Biomass Feedstock Logistics by Reducing ash and Moisture content
- Dias de Oliveira, Ezer Júnior and Fernando Seixas. Energy Analysis of two Eucalyptus Harvesting Systems in Brazil
- Dukes, C. Cory, W. Dale Greene and Shawn A. Baker. In-Woods screening of Grindings from Logging Residues to Improve Biomass feedstock Quality
- Goldbach, D. Fecon Woody Biomass Harvesting Solutions
- Han, Sang-Kyun, Han-Sup Han, William J. Elliot, William R. Coltrin and Bruce R. Hartsough. ThinTool: A spreadsheet model to evaluate fuel reduction thinning cost, biomass for energy, and nutrient removal
- Hartley, Damon S. and Jingxin Wang. Analysis of harvesting logistics on woody biomass

supply chains for community based bioenergy projects in West Virginia.

- Hiesl, Patrick and Jeffrey G. Benjamin. Cycle Time Analysis of Harvesting Equipment from an Early-Commercial-Thinning Treatment in Maine
- Hopkins, Chris and Joseph Roise. Microchiping Trials of Green versus Dry, Pine versus Hardwood:Measurement of Energy Efficiency and Productivity
- Jernigan, Patrick, Tom Gallagher, Mathew Smidt, Larry Teeter and Dana Mitchell. High Tonnage Harvesting and Skidding for Loblolly Pine Energy Plantations
- Kanzian, Christian, Martin Kühmaier, Jan Zazgornik and Karl Stampfer. Large scale multi-criteria optimization of forestry biomass supply networks
- Klepac, John and Bob Rummer. Off-Road Transport of Pinyon/Juniper
- Mitchell, Dana. Ups and Downs Associated with Implementing Shift Schedules on a Southern Harvesting Operation
- Morris, Brian C., W. Mike Aust and M. Chad Bolding. Bladed skid trail erosion prediction for the state of West Virginia using USLE and WEPP
- Murphy, Glen, Francisca Belart, Tom Kent and Pieter D. Kofman. Forecasting and Monitoring moisture content of Woody Biomass in Ireland and Oregon to improve supply Chain Economics
- Pan, Pengmin Timothy McDonald, Steve Taylor and John Fulton. Real-time Monitoring mass-Flow of Woodchips bases on Force Sensor
- Seixas, Fernando and João Luís Ferreira Batista. Use of Wheeled Harvesters and Excavators in Eucalyptus Harvesting in Brazil
- Thompson, Jason D., John Klepac and Wesley Sprinkle. Trucking Characteristics for an In-woods Biomass Chipping Operation
- Wear, Laura R., W. Mike Aust, M. Chad Bolding, Brian D. Strahm and C. Andrew Dolloff. Skid trail stream crossing closure BMPs affect stream sedimentation
- Wimer, Jeff and John Sessions. Single Wide Tires for Log Trucks

~ top ~
Return to Publications Homepage

Logging Cost Components in the US South

Shawn A. Baker[1] and W. Dale Greene[2]

Abstract

Accurate data on timber harvesting costs are not widely available, and cost estimates are often based on historic values and rules of thumb regarding cost components. We collected detailed business and cost data from 13 logging businesses across the US South to determine the actual cost breakdown for a sample of contractors. Five participants operated in the southeastern US and eight operated in the south central US. Each participant provided data on costs and production for calendar year 2010. Labor (30%) and hauling (21%) represent the greatest components of cost, while fuel costs were 14% of the total. Investment in new equipment has declined substantially in recent years based on the age of the equipment fleet currently in the woods. No substantial differences in costs were found between contractors operating in the two regions.

Introduction

In the southern United States, timber harvesting is performed primarily by small, independent contractors (Baker and Greene 2008). The efficient felling, processing and delivery of raw forest products require people skilled in operating businesses that rely on an increasingly expensive array of specialized machinery. There is no expectation of cost or profitability reporting, as is required of publicly traded companies, and collection of these data can be challenging. Forest harvesting contractors represent a vital link in the wood supply chain, yet relatively little data exist on the true costs associated with these businesses.

Many researchers have attempted to estimate costs based on publicly available information or easily attainable data. Matthews (1942) described the machine rate equations which have subsequently been used as a standard method for estimating and comparing costs of logging equipment (e.g. Miyata 1980, Werblow and Cubbage 1986, Brinker *et al.* 2002). Machine rate cost estimates require knowledge of a range of inputs (original purchase price, loan interest rates, fuel consumption, maintenance and repair costs, etc.), but when these values are not empirically known, estimated values or rules of thumb are often used to generate approximate costs (Burgess and Cubbage 1989a). Werblow and Cubbage (1984) used data from contractor and equipment company surveys to generate a table of average machine rates for common classes of forest machinery. This method was repeated periodically by other researchers to provide a

[1] Research Professional. Warnell School of Forestry and Natural Resources. University of Georgia. Athens, GA, USA 30602-2152. Corresponding author: Shawn Baker, ph. 1.706.542.4298, shbaker3@uga.edu
[2] Professor, Warnell School of Forestry and Natural Resources. University of Georgia. Athens, GA, USA 30602-2152. wdgreene@uga.edu

timeline of machine rates by which a rough estimate of changes in logging costs (those related to owning and operating machinery) could be estimated (Cubbage *et al.* 1988, Brinker *et al*. 2002). These data have not been revised since 2002.

The most detailed source of harvesting cost information for US logging operations over the past decade or more is likely the Contractor Cost and Productivity Survey described by Stuart *et al.* (2010). This dataset, first presented by Loving (1991) and subsequently updated (see Stuart and Grace 1999 and Stuart *et al.* 2008 for additional detail) has tracked a group of contractors ranging in number from 25 to 44, collecting detailed cost information from accounting records of each business. The data were used to generate a logging cost index from 1988 through 2006 which provided an empirical measure of changes in aggregate and component costs for harvesting businesses. Using Contractor Cost Survey data, Stuart *et al.* (2011) concluded that per ton logging costs have not changed appreciably in real terms over the past twenty years despite substantial shifts in the allocation of costs between the major cost categories (equipment, labor, consumables, insurance, overhead, and contracted services).

The approach used by Loving (1991) gathers empirical cost data for a sample of the industry and provides an ideal method to measure the costs incurred. A measure of changes in costs grounded in actual data provides a basis against which less intensive cost estimates can be compared. We report the percentage breakdown of costs incurred by a group of logging contractors in calendar year 2010. Where possible, we draw comparisons between our findings and published data from other sources.

Methods

Our effort focused on contractors working primarily in either the Southeastern US or in the South Central US. We worked with a cooperating company to identify contractors willing to participate in the project. An initial contact letter was sent by the cooperating company to contractors in these regions to inform them of the upcoming university research project. A follow-up letter was sent by the authors approximately two months later informing all contractors of the research project and requesting their assistance should they be contacted. We were provided a list of contact information and production data for all contractors operating in these regions with which the cooperating company had done business. We randomly selected 18 contractors from the 82 who harvested wood for the company during 2010 (22% sample).

Each selected contractor was contacted via phone to request participation. When contractors agreed to participate, face-to-face interviews were arranged using a questionnaire designed to gain general information on each company. In addition, detailed cost data from calendar year 2010 were requested. These data were collected from either profit and loss statements when available or 2010 tax returns. Identities of all participating contractors were kept confidential through use of numeric identification codes on any information gathered. Costs for separate logging crews operating within a single company were not available from the records of most of the participants. As a result, all values reported are for logging businesses and may comprise multiple logging crews, each with a different cost and production structure.

Costs were split into ten broad categories for comparison: Labor, equipment, interest expense, repair and maintenance, tires, fuel, other consumables, administrative, insurance, and hauling. In many instances contractors did not have specific cost data on “tires” or “other consumables”, in which cases these costs were assumed to be included in the “repair and maintenance” and “fuel” categories, respectively. Depreciation expenses were used to estimate annual equipment costs, rather than actual monthly payments. Payroll taxes were included as a labor expense, while workers compensation (if reported separately) was included in insurance.

Haul costs represented a substantial challenge as many companies distributed costs associated with trucks owned by the logging company across all cost categories for the business. Only the rates paid to contract haulers were separated as a ‘hauling’ cost in their records. From the detailed records of a few businesses, it was possible to separate the haul costs for both owned and contracted trucks. This average haul rate per ton is a higher percentage of total costs. The most accurate approach to estimate cut and load rates is likely to assume the average haul rate is representative for costs of all companies, though this method is imprecise as haul distances will vary between companies.

Results

Respondents

Out of the eighteen companies contacted, five were unwilling to participate in the study. The nonparticipants stated a reluctance to provide any financial information. Despite assurances that no uniquely identifiable information would be shared, the owners of these businesses saw no net potential benefit to participation.

We interviewed thirteen participating contractors, five in the Southeast region and eight in South Central. The median company had been in business 27 years, and was fairly large, with two crews per company, 14 total employees and 9 in the forest (Table 1). The average production of individual crews was 63 loads per week, with companies reporting average production of 153 loads per week. Production data from 2010 shows actual production averaged 133 loads per week.

The companies contracted 50% of their hauling to outside firms and supplied the remaining 50% with tractor-trailers owned by the company. A typical firm owned seven tractor-trailers (3.5 per crew). The median fuel mileage for company-owned tractor trailers was 5 mi/gal, which is consistent with other reports on heavy truck fuel consumption (Fender and Pierce 2011).

Table 1. Summary of respondent company information.

	Median	Range		
Years in business	27	5	--	43
Average weekly production (loads)	100	23	--	350
Perceived breakeven production (loads)	78	25	--	350
Number of logging crews	2	1	--	7
Total company employees	14	4	--	35
Total employees in woods	9	4	--	25
Number of markets	9	5	--	17
Average haul distance (miles)	60	20	--	65
Average off-road diesel consumption (gal/wk)	2200	400	--	4000
Average on-road diesel consumption (gal/wk)	1800	300	--	3500
Monthly non-fuel consumables cost ($)	1600	800	--	8000
Number of passenger trucks owned	4	3	--	10
Workers compensation insurance rate ($/ton)	0.33	0.27	--	0.39
Percent contract trucking	50%	0%	--	80%
Average tractor-trailer fuel mileage (mi/gal)	5	4.5	--	6.5
Number of tractor-trailers owned	7	1	--	22
Annual overweight fines ($)	1125	400	--	7500

Labor represented the largest source of cost for logging crews, averaging roughly 30% (Table 2). Reported haul costs averaged 21%, but estimates based on detailed trucking cost records suggest combined contract and company-owned haul costs are closer to 30%. Firms which primarily performed their own trucking, but did not separate their costs for owning and operating trucks from their in-woods harvesting costs had a much lower percentage of costs represented as “Hauling”. Fuel costs represented 14% of total cost in respondent companies, but varied between roughly 10 and 20%. Much of this variation is explained by the inclusion of fuel for trucks owned by the company in this category (rather than as a “Hauling” cost). Repair and maintenance cost was a highly variable category for respondents, ranging from 3% to 18%.

Respondents in the two regions, coastal plain and Piedmont, reported similar cost breakdowns (Table 3). The only major difference was a higher fuel cost in coastal plain and a higher hauling cost in the Piedmont. This is explained by a higher percentage of contract hauling in Piedmont contractors (73% vs. 30%), where the costs of a significant portion of the trucking fuel was not recorded in the companies’ fuel costs.

Table 2. Breakdown of costs categories to cut and haul roundwood for respondent logging contractors.

Cost Category	Total Cost (%)	Low	High
Labor	30%	25%	35%
Depreciation	14%	9%	20%
Interest Expense	3%	0.3%	5%
Repair & Maintenance	12%	3%	18%
Fuel	14%	12%	22%
Administrative	3%	1%	4%
Insurance	5%	2%	7%
Hauling	21%	5%	29%

Table 3. Breakdown of costs categories for contractors operating in the coastal plain and Piedmont.

	Coastal Plain	Piedmont
Labor	31%	29%
Depreciation	14%	14%
Interest Expense	2%	3%
Repair & Maintenance	11%	12%
Fuel	17%	13%
Administrative	2%	4%
Insurance	7%	4%
Hauling	16%	22%
Total	100%	100%

Consumables

On-road diesel prices averaged $3.01 for calendar year 2010 (EIA 2011). Over this timeframe, contractors spent roughly 14% of total wood cost on petroleum-based consumables (both on- and off-road fuel, grease, oil, etc.). This fuel consumption included some fuel purchases for trucks owned by the contractors, but did not include fuel consumption by contract haulers. Off-road diesel consumption reported by participants averaged roughly 0.57 gallons per ton. This value falls within the range of previous studies on fuel consumption in tree-length harvesting operations reported by McNeill *et al*. (2010). Information on actual consumption was not available from some contractors, as few maintained detailed fuel consumption records. Comparisons between groups of contractors based on average fuel cost per ton were therefore not meaningful because few differentiated off-road and on-road diesel purchases in financial records. Thus fuel used in trucking confounds the fuel consumption differences from harvesting operations.

On-road diesel consumption was gleaned from responses to the surveys and averaged 5 miles per gallon with a 50 mile average haul distance. This corresponds to 0.73 gallons per ton (average payload of 27.5 tons) or $0.60 per mile for fuel ($3.01 per gallon and 5 mpg). The American Transportation Research Institute report on over-the-road trucking costs in the first quarter of 2010 reported average fuel and oil costs of $0.465/mile (Fender and Pierce 2011). Given that logging trucks are on lower standard roads traveling at slower speeds that reduce fuel mileage, this difference of about 30 percent does not seem unreasonable. An increase in fuel mileage from 5 to 6 mpg would largely explain this difference.

Equipment

Annual interest expense varied from 1-6% of total costs. Interest rates for machinery financed by equipment companies were reported at extremely low levels (some respondents cited rates as low as 2%). This may explain a portion of the low interest expense, especially for the contractors who reported higher depreciation costs (i.e. newer equipment). Equipment companies have offered extremely low financing rates since the recession started in 2008 to help sell equipment but were forced to be selective about whom to finance.

Only 21 out of the 114 pieces of production equipment (18%) reported in use by the contractors were model year '09 or newer (this excludes "spare" equipment not in use on a daily basis). Thus, 82% of the equipment in use in the woods has over two and a half years of wear on it (Figure 1). Many contractors reported replacing equipment based on downtime and repair costs, though a select few based decisions primarily on machine hours and warranty coverage. The poor market conditions of the past three years have made contractors reluctant to purchase machinery, pushing many beyond the point where they would ordinarily replace some of their equipment.

Figure 1. Number of machines in use by model year for survey respondents. Age data were not available for six machines.

Production

Production variability is often cited as a major factor contributing to harvesting costs. With fixed costs representing around half of total delivered cost, this is a reasonable claim. Increases in production allow for a reduction in per ton fixed costs. Minimizing production variability also minimizes cost variability (Greene *et al.* 2004). Responding loggers averaged 23.5% coefficient of variation (CV) on weekly tons delivered in 2010. The CV varied from 15 to 38% between companies.

During interviews, we discussed the role of production quotas (restrictive wood orders) at length. Many contractors reported having no negative impacts to their operations as a result of quotas during the previous calendar year, while others stated that limited quotas were a negative impact and often a factor every week. The wide range in CV for production supports the claims of widely variant effects as a result of quotas.

Non-Cost Survey Results

In addition to the cost category data, a number of respondents spoke generally about the business environment within which they operate. The timing of this study, at the end of two years of severe recession in the economy as a whole (as well as particularly severe impacts to much of the forest industry), is reflected by the comments of many of the respondents. A portion were concerned about the rates they were receiving, feeling that their profit was not sufficient to maintain the business.

Despite close scrutiny of the data gathered, we could not find any reliable indicators of characteristics shared by "good" business-people. Discussions with owner-operators clearly revealed however that some had a greater aptitude for managing their business in the challenging economic climate, including a clear understanding of the cost and profit drivers for their business. A common lament was that the owners had invested in a business which now had little to no value and was generating little profit, signifying they had both minimal benefit from getting out of the business and little from staying in. The contrast with those owners whose businesses were struggling but still in solid financial condition was striking. From the limited dataset we gathered, no clear patterns emerged indicating why/how contractors shifted into one of these categories.

Discussion

This survey involved an examination of a group of contractors at a single point in time. To examine harvesting cost inflationary factors, a comparison to cost trends over time is necessary. While the data presented above do not allow a direct analysis over time, we compared them against existing datasets to determine if any substantial shifts in the cost distribution had occurred.

The overall breakdown of costs agreed very closely with the percentages reported by Stuart (2008) as Southwide harvesting costs in 2006 (Table 4). Stuart *et al.* (2008) includes workers compensation in "labor" costs and combines depreciation and interest as "equipment" costs. "Consumables" includes repair and maintenance costs as well as fuel and equipment that is expensed. "Administrative" costs include office personnel salaries and "contract services" may include contracted road and BMP costs in addition to contract trucking. We re-categorized our data to match the categories defined by Stuart (2008) to allow for a more direct comparison. The largest components of costs were in agreement.

Table 4. Cost breakdown of survey respondents in 2010 compared with reported cost breakdown for harvesting contractors across the South in 2006 using the cost categories used by Stuart *et al.*(2008).

Cost Component	Stuart *et al*. 2008	Baker and Greene, 2012
Labor	29%	30%
Equipment	15%	14%
Consumables	25%	27%
Administrative	3%	3%
Insurance	3%	5%
Contract Services	25%	21%

The participants in the current study were willing volunteers randomly selected from the population of loggers working with one company, while the sample of loggers used by Stuart *et al.* (2008) was not designed to be a representative or random sample, but was a subjective selection of willing contractors who the authors categorize as small (less than 50,000 tons/yr), medium (50-140,000 tons/yr), or high production (140,000+ tons/yr), with roughly equal proportions in each category. Roughly one-third of the firms are in each production category to provide equal representation. By the same measures, the contractors in this survey were roughly 10% small, 45% medium and 45% high production. By comparison, a survey of Georgia logging contractors found respondents comprised of 40% small, 50% medium, and 10% large contractors using the same production criteria (Baker and Greene 2008). As such, the averages reported here and by Stuart and Grace (2011) are not necessarily accurate Southwide averages because the percentage of high production contractors is much lower across the South than the percentage of smaller contractors. High production crews do however represent a greater proportion of the total tons harvested across the South.

Follow up work is needed to determine how a similar random sample of southern logging contractors will respond to changes in cost components over a period of years. Additional efforts are also needed to compare the accuracy of current logging cost estimation techniques using widely accepted values and rules-of-thumb against actual costs.

Acknowledgements

The authors wish to thank all of the contractors who shared their information during this study, without whose cooperation we would have no data.

References

Baker, S.A., Greene, W.D.. 2008., Changes in Georgia's Logging Workforce: 1987-2007. Southern Journal of Applied Forestry 32(2): 60-68.

Brinker, R.W., Kinard, J., Rummer, B., Lanford, B., 2002. Machine Rates for Selected Forest Harvesting Machines. Auburn, AL. Alabama Experiment Station.

Burgess, J.A.; Cubbage, F.W. 1989a. Comparison of machine rate and cash flow approaches for estimating forest harvesting equipment costs. Paper 89-7548. Presented at the 1989 Meeting of the American Society of Agricultural Engineers. St. Joseph, MI: ASAE. 24 p.

Cubbage, F.W, Stokes, B.J., and Granskog, J.E. 1988. Trends in southern forest harvesting equipment and logging costs. Southern Journal of Applied Forestry. 38(2): 6-10.

Energy Information Agency. 2011. Los Angeles, CA Ultra-low sulfur CARB diesel spot price (dollars per gallon). Available from: http://tonto.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=EER_EPD2DC_PF4_Y05LA_DPG&f=M Last accessed on: August 18, 2011.

Fender, K.J., Pierce, D.A., 2011. An analysis of the operational costs of trucking: A 2011 update. American Transportation Research Institute, Arlington, VA. 25 p.

Greene, W.D., Mayo, J.F., deHoop, C.F., Egan, A.F., 2004. Causes and cost of unused logging capacity in the southern United States and Maine. Forest Products Journal 54(5).

Loving, R.E., 1991. Components of logging costs. M.S. thesis. Virginia Polytechnic Institute and State University. 204 p.

Matthews, D.M., 1942. Cost control in the logging industry. New York: McGraw-Hill Company.

Miyata, E.S., 1980. Determining fixed and operating costs of logging equipment. . US Dept. of Agriculture, Forest Service, North Central Forest Experiment Station. 16 p.

McNeill, J., Greene, W.D., Baker, S.A., 2010. Off-road diesel fuel consumption for logging operations. Technical Release 10-R-9. Forest Resources Association. Rockville, MD. 2p.

Stuart, W.B. and Grace, L.A. 2011. The logging cost index. Forest Operations Review 13(2): 9-15.

Stuart, W.B. and Grace, L.A. 1999. Wood supplier productivity and cost survey. Technical paper 99-A-7. Rockville, MD: American Pulpwood Association. 46 p.

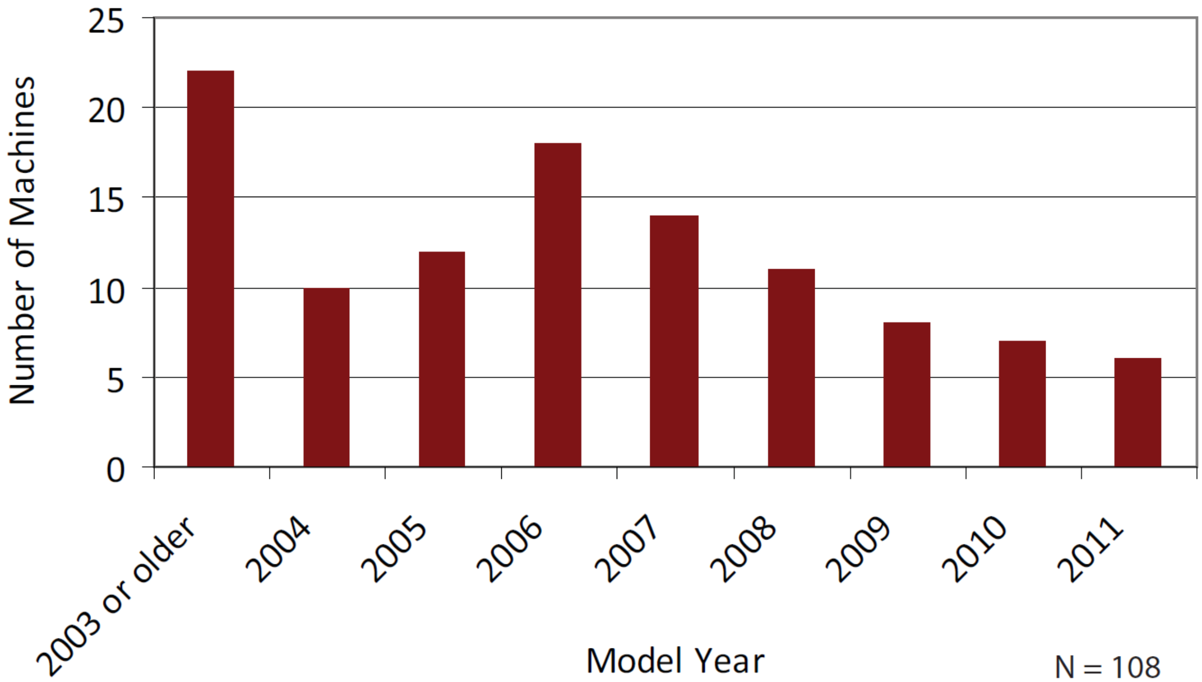
Stuart, W.B., Grace, L.A., and Grala, R.K. 2010. Returns to scale in the Eastern United States logging industry. Forest Policy and Economics. 12: 451-456.

Stuart, W.B., Grace, L.A., Altizer, C.B., Smith, J.J., 2008. 2006 Preliminary Logging Cost Indices. Wood Supply Research Institute. Forest and Wildlife Research Center, Starkville, MS. #FO387. 14 p.

Stuart, W.B., Grace, L.A., Jackson, B.D., Stutzman, R., 2003. Logging Cost Indices: First quarterly report to the Wood Supply Research Institute. Forest and Wildlife Research Center, Starkville, MS. #FO225. 21 p.

Werblow, D.A., Cubbage, F.W., 1986. Forest harvesting equipment ownership and operating costs in 1984. Southern Journal of Applied Forestry 10(1): 10-15.

Figure 1. Number of machines in use by model year for survey respondents. Age data were not available for six machines.



USE OF WHEELED HARVESTERS AND EXCAVATORS IN EUCALYPTUS HARVESTING IN BRAZIL

Fernando Seixas[1] and João Luís Ferreira Batista[2]

Abstract

Excavators are commonly used in forest harvesting in Brazil as an option to typical forestry harvesters, mainly because of lower cost and some models being fabricated locally, which means more units sold, facilitating dealer's support and parts purchase. Problems with excavators are related to high cost of tracks maintenance and difficulties to operate on steep ground terrain, when compared with wheeled harvesters. This study compared excavators, utilized as forestry harvesters, with wheeled harvesters felling trees in Eucalyptus plantation located on flat terrain. The machine's productivities were quite similar, but the higher cost per effective hour of wheeled harvesters, concerned the models utilized in this study, favored the use of excavators, as base machines, to fell trees in a clear-cut system on flat terrain.

Keywords: harvesting; forestry mechanization.

Introduction

"Cut-to-length" systems are those in which all operations are done inside the stand, with logs being prepared in 1-6 m in length for extraction. These systems were mainly developed in Scandinavia (ANDERSSON; LAESTADIUS, 1987), where about 90% of timber were harvested in the form of short logs (MAKKONEN, 1989), mainly through the harvester plus forwarder module.
These are also the major timber harvesting systems used in Brazil, with 129 harvesters and 191 forwarders sold during the 90s, compared with 45 feller bunchers and 105 skidders (SANTOS, 2000). In 2005, manufacturers sold 200 machines to "cut-to-length" systems and only 20 units to "tree-length" systems (MACEDO, 2006).
In a survey conducted in 2006, with nine Brazilian forest companies, with an average annual consumption of 3.0 million m^3 of timber per company, three companies used only "cut-to-length" systems (harvester + forwarder), two companies worked only with "tree-length" systems (feller buncher + skidder), and the other four used both systems simultaneously. These companies together had 113 harvesters, with 90 excavators as base machine, and 12 units working like processors, 50 forwarders, 25 feller bunchers, 35 skidders, and 14 clambunk skidders (SEIXAS, 2006).
Harvesters are machines with tires or mats, or even adjustments made in crawler excavators with the placement of a head processor. The latter option is widely used in the Brazilian forest sector, mainly due to lower cost of acquisition and the existence of models manufactured in the country, facilitating technical assistance and purchase of parts and maintenance. Counterarguments refer to the high cost of maintenance of the conveyor

[1] Professor, ESALQ/USP, Piracicaba, SP, Brazil. E-mail: fseixas@usp.br
[2] Professor, ESALQ/USP, Piracicaba, SP, Brazil. E-mail: parsival@usp.br

and a greater restriction on the operation on rough terrain, in comparison with wheeled machines.
Johansson (1995) concluded that three types of adapted excavators, working as harvesters, yield similar to specialized forestry equipment (wheeled harvesters), but with lower operating costs because of lower purchase price. Spencer (1992) points out that this type of adapted machine has some limitations to work on clear cutting on steep ground terrain, more likely, not exceeding 38% slope "uphill" and 20% "downhill" with the volume per tree of maximum 0.5 m^3. Simões and Fenner (2010), analyzing a John Deere 200C LC excavator equipped with Waratah H270 processor head, determined that the harvester productivity decreased by 36.4%, when moving the operation from a terrain with slopes in the range 10 to 13% (35.4 $m^3.h^{-1}$) to another area with a slope in the range 21 to 25% (22.5 $m^3.h^{-1}$).

Therefore, this study aimed to compare, in terms of technical and economic aspects, the use of wheeled harvesters and adapted crawler excavators cutting trees in eucalyptus stands.

Materials and Methods

Local and equipments

This survey included the participation of four forest companies that have provided the opportunity to collect data on their eucalyptus forests. The technical descriptions and the number of each type of studied machine are shown in Table 1, as well as the mean value of service life (hours). These machines worked in *Eucalyptus urograndis* stands, located on flat terrain (slope: 0-10%), and no precipitation occurred during the data collection. The trees were processed into 6.0 m logs, and all operators had an average experience over 2 years, but the conditions of forest productivity were different, as well as the spacing, as seen in Table 2.

TABLE 1: Technical characteristics of harvesters utilized in this study

	Harvesters			
Characteristics	Komatsu PC228	Volvo EC 210 B	Valmet 941.1	John Deere 1270
Configuration	Tracks	Tracks	Tires	Tires
Power (kW)	116	107	210	160
Weight (t)	22.9	21.6	25.9	17.5
Crane reach (m)	8.0	9.9	10.0	9.3
Processor head	Valmet 370E	Valmet 370E	Valmet 370E	H 270E
Odometer (h)*	5,294	15,272	6,416	22,407
N° of machines	3	10	4	2

* Average values.

Time and motion study

The felling operation was followed in 1-hour cycles, recording the beginning and end of each cycle, through a multimoment system collecting data every 10 seconds. The following activities were observed: a) cutting; b) bucking; c) delimbing; d) debarking; e) harvester movement; f) crane movement; g) technical pause h) personal pause. It was recorded the number of trees cut per cycle and productivity (m^3 per effective hour of work), and obtained, by the company that owns the machine, the mechanical availability and operational efficiency of the observed harvester. The planting space was not considered because, according to Martins et al. (2009), the average volume per tree explains 88.0% of harvester operational capacity, while the spacing affects only 8.5%.

Operational cost

The determination of the operational cost was made by the method described by Sessions (1987), obtaining a theoretical value which allowed the comparison of all machines. The final comparison between wheeled harvester and adapted excavator was made from the yield in number of trees per effective hour per machine, assuming a single average volume per tree among all sites, and the average cost per time for different models of harvester.

Statistical analysis

Linear (straight line) and parabolic models were tested, by linear regression, to represent the relationship between the average size of trees (m^3) and the productivity of tractors ($m^3.h^{-1}$). The influence of the wheel set (crawler / tire) was introduced in the models as indicator variable, testing the statistical significance of the interaction of the type of wheel set with the model parameters. The influence of the tractor, in the type of wheel set, was regarded as a random effect, thus transforming the classical linear model into mixed effects linear model. The mixed effects model was adjusted according to the approach proposed by Pinheiro and Battes (2004). The adjusted models were compared using the Akaike Information Criterion (A.I.C.), as presented by Burnham and Anderson (1998). The construction and comparison of models was performed in R software (R Development Core Team, 2008).

Results

Two models of "track harvesters" were followed, Komatsu PC228 U.S. and Volvo EC210 B, with a total of 117 1-hour samples, and two models of “wheel harvesters”, John Deere 1270 and Valmet 941.1, with 34 cycles (Table 2). The smaller number of samples for the "wheel harvesters" already reflects the companies’ choice by excavators to operate on flat terrain (slope: 0-10%). The mean values for excavators and wheeled harvesters were, respectively, 19.52 $m^3.h^{-1}$ and 24.34 $m^3.h^{-1}$, statistically different from each other.

TABLE 2: Harvesters operational capacity and cost per m^3.

	Harvesters				
Characteristic	Komatsu PC228	Volvo EC 210 B	Volvo EC 210 B	Valmet 941.1	John Deere 1270
Productivity ($m^3.h^{-1}$)	36.05	12.70	28.76	26.53	19.07
Volume ($m^3.tree^{-1}$)	0.46	0.22	0.33	0.35	0.29
N°trees.h^{-1}	78	54	87	76	66
Spacing	5.0 x 2.4 m	3.0 x 2.0 m	3.0 x 2.5 m	3.0 x 2.5 m	3.0 x 2.5 m
Availability (%)	67	71	71	65	57
Hourly cost ($\$.h^{-1}$)	96.00	84.61	84.61	136.30	132.80
Cost ($\$.m^{-3}$)	2.66	6.66	2.94	5.14	6.96
N°of cycles	28	80	9	24	10

By modeling the relationship between the average volume of trees (m^3) and harvesters' productivity ($m^3.h^{-1}$), the parabolic model proved be clearly superior to simple linear model (straight line), as can be seen in Table 3. The wheel set (track or tire) influence showed also a marked improvement in the quality of explanatory models, in case of the model (2) compared to models (3) and (4) (Table 3). However, only the interaction with the intercept was also relevant (model (3) compared to the model (4)). Finally, the inclusion of tractor model random effect in the wheel set type (track or tire), showed that this random effect is also relevant for explaining the data, resulting in the best model found (model (5)) (Table 3).

TABLE 3: Comparison among linear and parabolic models for relationship between average tree volume (m^3) and harvesters' productivity ($m^3.h^{-1}$).

Models	Freedom Degrees	A.I.C.
(1) Simple Linear Model	3	848.46
(2) Parabolic Model	4	835.85
(3) Parabolic Model with Wheel Set x Intercept Term Interaction	5	829.48
(4) Parabolic Model with Wheel Set x All Terms (intercept, linear, parabolic) Interaction	7	831.80
(5) Parabolic Model with Wheel Set x Intercept Term Interaction and Tractor Model Random Effect in the Wheel Set Type	6	816.50

The relationship between the productivity of the tractor and the average size of trees is a curvilinear model (parabola), in other words, increasing the average volume of trees also increases the machine’s productivity, but the rate of growth decreases gradually and tends to stabilize. The type of wheel set (track or tire) had a clear influence on the "level" of the curve (model intercept term), but did not influence the rate of growth (linear term of the model), or the curvature of growth (parabolic term of model). It was also observed that the tractor models insert variability in productivity response to the increase of the average size of trees, but this variability was not sufficient to mask the effect of the type of wheel set (track or tire). These effects are displayed in Figure 1.

This degree of correlation is supported by several studies with “cut-to-length” harvesting systems, in which as the volume per tree increased productivity also increased, and, consequently, the production costs decreased (BULLEY, 1999; GINGRAS, 1996; ELIASSON, 1999; MACHADO et al., 2002; RICHARDSON; MAKKONEN, 1994; SILVA; MACHADO, 1995).

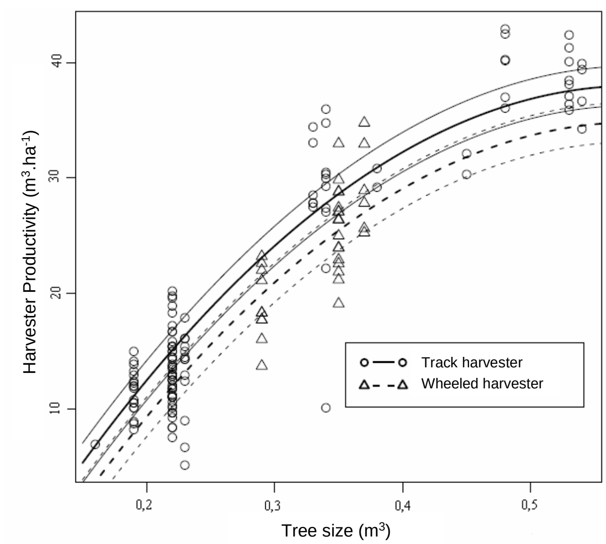


FIGURE 1: Linear regression for harvesters and excavators productivity ($m^3.h^{-1}$) as a function of average tree volume (m^3).

The found values of cost per m^3 also differed depending on the model of harvester, and the average volume of timber per tree. To facilitate comparison between harvester models, with tracks or tires, it was considered the average volume of 0.33 m^3 per tree to all situations. The yield was calculated at 23.4 $m^3.h^{-1}$ for the wheeled harvesters, and 24.5 $m^3.h^{-1}$ for track harvesters, quite similar values, but average costs per m^3 were different, with $3.70 for track harvesters, and $5.77 for harvesters with tires, endorsing the decision of the majority of forest companies adopting excavators as base machine for cutting trees on flat terrain, due to lower cost per m^3.

In the case of time and motion study, the percentage of time spent with debarking and delimbing was higher for harvesters with tires and powerful engines, and the bucking activity spent more time in the operation of track machines, but it was not found the reason of these two unique differences and the productivity influence (Table 4).

TABLE 4: Average values (%) for harvesters and excavators activities.

Harvester	Activities						
	Felling	Bucking	Debarking/ Delimbing	Harvester movement	Crane movement	Technical Pause	Personal Pause
Tracks	16.6	34.8	22.4	3.9	13.5	6.9	2.0
Tires	14.4	24.9	29.9	6.2	14.6	8.6	1.4

Conclusions

The highest hourly cost of wheeled harvesters, working under the conditions of this study, favored the use of excavators as base machines in the tree felling operation, in forest stands located on flat ground terrain, with both harvesters' models showing similar productivities on forests consisting of trees with same individual volume.

References

ANDERSSON, S.; LAESTADIUS, L. Efficiency in highly mechanized wood harvesting systems. In: SIMPÓSIO SOBRE EXPLORAÇÃO, TRANSPORTE, ERGONOMIA E SEGURANÇA EM REFLORESTAMENTOS. Curitiba: UFPR - FUPEF, 1987. p. 133-43.

BULLEY, B. Effect of tree size and stand density on harvester and forwarder productivity in commercial thinning. **FERIC Technical Note**, n. 292, p. 1-8, jul. 1999.

BURHAM, K. P.; ANDERSON, D. R. **Model selection and multimodel inference: a pratical information-theoretic approach**. New York: Springer-Verlag. 2002, 488 p.
ELIASSON, L. Simulation of thinning with a single-grip harvester. **Forest Science** 45(1) 1999. p. 26-34.

GINGRAS, J. F. Evaluation of logmax harvester heads in Nova Scotia. **FERIC, Field note** n 26. October 1996.
JOHANSSON, J. Excavators as base machines in logging operations. **Journal of Forest Engineering**, Fredericton, vol. 7, n. 1, p. 7-17, 1995.

MACEDO, R. Mecanização florestal na medida certa. **Referência**, Curitiba, ano 8, n. 58, p. 23-46, ago. 2006.

MACHADO C.C. *et al.* Análise de custo de subsistemas de colheita de toras de eucalipto de diferentes comprimentos e volumes por árvore. **Revista Árvore**, Viçosa, v.26, n.1, p.73-81, 2002.

MAKKONEN, I. Evaluation of Timberjack 230 8-ton forwarder. FERIC Technical Note 140. FERIC Pointe Claire, 6 p., 1989.

MARTINS, R.J.; SEIXAS, F.; STAPE, J.L. Avaliação técnica e econômica de um *harvester* trabalhando em diferentes condições de espaçamento e arranjo de plantio em povoamento de eucalipto. **Scientia Forestalis**, Piracicaba, v. 37, n. 83, p. 253-263, set. 2009.

PINHEIRO, J.S.; BATES, D.M. **Mixed-Effects Models in S and S-SPLUS**. New York: Springer-Verlag. 2009, 530 P.

R DEVELOPMENT CORE TEAM. R: A language and environment for statistical computing. Viena: R Foundation for Statistical Computing, 2008. Disponível em: <http://www.R-project.org>. Accessed on: july 29, 2010.

RICHARDSON, R.; MAKKONEN, I. The performance of cut-to-length systems in Eastern Canada. **FERIC Technical Report**, n. 109, p. 1-16, nov. 1994.

SEIXAS, F. Levantamento sobre máquinas florestais. Piracicaba: ESALQ, 2 p. 2006 (não publicado).

SESSIONS, J. Cost control in logging and road construction. In: FAO – Appropriate wood harvesting in plantation forests. FAO Forestry Paper 78, Rome, p. 95-134. 1987.

SILVA, L.M. da, MACHADO, C.C. Influência do diâmetro e do número de árvores por hectare no custo de corte do eucalipto. **Revista Árvore,** Viçosa, v.19, n.3, p.308-318, 1995.

SIMÕES, D.; FENNER, P.T. Influência do relevo na produtividade e custos do “harvester”. **Scientia Forestalis**, Piracicaba, v.38, n. 85, p. 107-114, 2010.

SPENCER, J.B. Slope limits for excavator based clearfell and thinning harvesters. Technical development branch. Forestry Comission, Great Britain, Technical Note 4/92, 1992. 12 p.

Ant Colony Optimization for Road Modifications

Storm Beck[1] and John Sessions[2]

Abstract

Non-conventional products provide opportunities for the forest industry to increase economic value from forests; however, these products may require specialized or non-standard vehicles to transport these products. The existing forest transportation network was not necessarily designed to the road standards required for these non-standard vehicles. Several options are available to forest managers to allow these vehicles to navigate the forest transportation network including filling the ditch, removing the superelevation, reversing the superelevation, or even reconstructing the roadway. For each investment, there is an associated vehicle that can traverse the road segment if the investment is made. This paper uses the ant colony heuristic to identify the optimal vehicle choice and road modification option to effectively transport non-conventional products.

Keywords: Ant Colony Optimization, Biomass Transport, Vehicle Accessibility

Introduction

The production of high valued non-conventional products, such as utility poles or the production of low valued products such as chips or hogfuel, provide opportunities for the forestry industry to increase economic value from forests. However, most of the forest transportation system has been designed and built for long-log, stinger-steered trailers (Sessions et al., 2010) and there is little engineering record of road design or location throughout the forest industry (Craven et al., 2011). For example the 15,000 acre OSU College Forests and the 70,000 acre Starker Forests have no data on the horizontal, vertical, or cross-sections of their roads (Lysne and Klumph, 2011; Beathe, 2011). This lack of engineering records provides a challenging environment in the assessment for transporting non-conventional products. The primary challenge to hauling non-conventional products, on non-standard vehicles, is determining if the vehicle can navigate the horizontal and vertical geometry unloaded and loaded, as well as turning around near the landing. These non-standard vehicles include pole trailers with rear self-steering axles, pole trailers with stinger-steered axles, fifth-wheel chip vans (with and without self-steering rear axles), and stinger-steered chip vans. We define a pole trailer as a stinger-steered trailer with a bunk-to-bunk distance longer than 28 feet, hauling logs that are longer than 45 feet.

[1] Department of Forest Engineering, Resources and Management. Oregon State University. Corvallis, Oregon 9733. storm.beck@oregonstate.edu
[2] Department of Forest Engineering, Resources and Management. Oregon State University. Corvallis, Oregon 9733. john.sessions@oregonstate.edu

Problem Description

Several choices affect the accessibility of these non-standard vehicles. These choices include temporarily filling the ditch, removing or reversing the superelevation to reduce lateral tire slip, and widening the roadway. During the dry months, temporarily filling the ditches or changing the superelevation of the roadway are options that permit non-standard vehicles access. Temporarily filling the ditch provides a greater road width for the non-standard vehicle to pass, usually two to five feet of extra road width. Superelevation of the road surface is constructed into forest roads to drain water from the road surface. During the dry months, superelevation is not needed; providing an opportunity to alter the superelevation to reduce lateral tire slip toward the inside of a curve. Two options exist when altering the superelevation (1) remove the superelevation and (2) reverse the superelevation. Removing the superelevation reduces the amount of off-tracking that a vehicle produces by reducing the amount of lateral tire slip due to gravity. Reversing the superelevation could be used to counteract off-tracking; allowing the weight of the vehicle and the effects of gravity on an inclined plane to counter the effects of off-tracking. Lastly, forest engineers and managers can affect the outcome by redesigning the roadway to allow these vehicles access along the entire length. This is achieved by widening the roadway and removing obstacles close to the roadway such as standing trees.

Each modification option has an associated cost and benefit. For example, if a 45-ft drop center 5th-wheel chip van needs an extra 2 feet of road width to access a harvest unit, the ditches might be temporarily filled to allow the 5th-wheel chip van access. If the ditches were not filled, the only vehicle that might have access to the unit would be a stinger-steered chip trailer. Not only does the amount of off-tracking vary between vehicles, so does the volume of chips or hogfuel consistent with weight restrictions that these vehicles can haul. The operating cost and traveling speed vary for each vehicle configuration, creating a multi-dimensional problem. Mixed integer linear programming can be used to solve the underlying mathematical problem for small problems. As an alternative solution method, this paper looks at the use of Ant Colony Optimization (ACO) to determine the optimal vehicle type, path, and road modifications for transporting biomass.

Mathematical Formulation

The mathematical problem is to minimize the sum of road modifications and biomass transportation costs. Let G=(N,A) be a directed network with nodes N and arcs (i,j) within A. We associate with each node i within N a number S(i) which indicates the supply or demand depending on whether S(i) > 0 or S(i) < 0. The minimal cost problem is then

Minimize

$$\sum_{(i,j)\in A} FC_{ij}^t * Y_{ij}^t + \sum_{(i,j)\in A}\sum_{t\in T} VC_{ij}^t * Volume_{ij}^t \quad \forall\ (i,j)\in A, t\in T \qquad (1)$$

Conservation of Flow

$$\sum_{\{ji(i,j)\in A\}} Volume_{ij}^{t} - \sum_{\{ji(j,i)\in A\}} Volume_{ji}^{t} = V^{t}(i) \quad \forall\, i \in N \tag{2}$$

Sale Volumes

$$\sum_{t\in T} V^{t}(i) = S(i) \qquad \forall\; i \in N \tag{3}$$

Road Triggers

$$\sum_{t\in T} M * Y_{ij}^{t} \geq Volume_{ij}^{1} \qquad \forall\,(i,j) \in A \tag{4}$$

$$\sum_{t\in T\,(t\geq 2)} M * Y_{ij}^{t} \geq Volume_{ij}^{2} \qquad \forall\,(i,j) \in A \tag{5}$$

$$\sum_{t\in T\,(t=3)} M * Y_{ij}^{t} \geq Volume_{ij}^{3} \qquad \forall\,(i,j) \in A \tag{6}$$

Decision Variables

$$Y_{ij}^{t} = \{0,1\} \qquad \forall\,(i,j) \in A, t \in T \tag{7}$$

$$Volume_{ij}^{t} \geq 0 \qquad \forall\,(i,j) \in A, t \in T \tag{8}$$

Equation (1) is the objective function. FC_{ij}^{t} is the fixed cost to modify link *ij* to allow truck type *t* access. Y_{ij}^{t} is a binary variable, zero if the link is not used, and one if the link is used. VC_{ij}^{t} is the variable cost over link *ij* in truck type *t,* ($/ton). $Volume_{ij}^{t}$ is the amount of volume crossing link *ij* in truck type *t,* (tons). Equation (2) provides conservation of flow at each node for each truck type. $V^{t}(i)$ is the volume entering each node *i* for each truck type *t,* (tons). Equation (3) requires that the total supply or demand at each node $S(i)$ (tons), equal the sum of the volume transported over all truck types. Equation (4) requires that the road modification for truck type *1* (the lowest standard truck type) be made to at least pass truck type *1* if there is volume passing over link *ij* in truck type *1*. Equation (5) requires that the road modification for truck type *2* (the moderate standard truck type) be made to at least pass truck type *2* if there is volume passing over link *ij* in truck type *2.* Equation (6) requires that the road modification for truck type *3* (the highest standard truck type) be made to pass truck type *3* if there is volume passing over link *ij* in truck type *3.* Equation (7) requires that the road trigger for link *ij* for truck type *t* be a binary variable, zero or one. Equation (8) requires that the volume passing over link *ij* for truck type *t* be equal to or greater than zero.

Review of Ant Colony Optimization

The ACO (Dorigo and Stuzle, 2004) is based on the analogy of ants searching for food. Ants randomly walk in search of food leaving a pheromone behind as they travel. The pheromone is a scent that influences other ants to take that path. As more ants travel over the same path the pheromone increases, increasing the possibility of an ant choosing that path. This process continues until all ants are following the same path to the food source. The ACO heuristic has been used to solve fixed cost and variable cost forest transportation problems with side constraints (Contreras, Chung, and Jones, 2008; Sessions, 1985). Outside of the forest industry, this heuristic has been used to solve vehicle route scheduling problems, capacitated vehicle routing problems, and scheduling problems (Donati et al. 2008; Rizzoli et al., 2007).

Ant Colony Optimization

The ACO developed in this paper is designed to minimize the total transportation cost. The total transportation cost is the sum of the modifications costs plus the variable costs multiplied by the volume of each harvest unit. If a truck is loaded at sale *x*, it must make it to destination *z* using the same truck. If different types of trucks use the same link, the one with the maximum fixed cost will be applied. Therefore, if road modifications are applied so that a 53-ft drop center 5th-wheel chip van can navigate the road, no other modifications need to take place for other truck types. The ACO regards each road modification option as a separate link. In other words, between each node three links exist; one that has no fixed cost, one that has a moderate fixed cost, and one that has a large fixed cost; all of which end up at the same node (Figure 1). As the algorithm progresses through each set of ants, each ant in each set has a designated modification option that it will choose from as it progresses through the network. It was chosen to have three kinds of ants; a truck type *1* ant, a truck type *2* ant, and a truck type *3* ant to diversify the search. With this formulation, each modification option has its own set of pheromones. The starting pheromones provided an equal probability choosing each link leaving a node for each truck type. As the algorithm identifies a lower total cost route from each sale, the links that are not part of that path have their pheromones decay. We use a constant decay factor of 25 percent.

The ACO was compared to a mixed integer linear programming model, using a small network (Figure 1). The large black circles are the nodes in the network. The small black circles are the road modification option for the 53-ft drop center 5th-wheel chip van, the small horizontally hatched circles are the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles are the no road modification option for the stinger-steered chip van. In this formulation, three different degrees of road modification could be applied, no modification, moderate modification, or severe modification. The no modification option will only allow a stinger-steered chip van access. The moderate modification option will allow a stinger-steered chip van and a 45-ft drop center 5th-wheel chip van access. The severe modification will allow all three trucks access to the road segment. Each truck has a different hourly operating cost. The stinger-steered chip van has an estimated hourly cost is \$95.37, the 45-ft drop center 5th-wheel chip van hourly cost is \$90.95, and the 53-ft drop center 5th-wheel chip van hourly cost is \$99.79 (Table 1). We assumed cost per hour did not vary with speed or road type.

The modification costs vary on the severity of the required modifications. The moderate modification option was assumed to require removing the superelevation within the roadway and filling the ditches to allow the 45-ft drop center 5th-wheel chip van access. We assumed that these modifications would cost $100 per station for half of the length of the link. The severe modification option was assumed to require filling the ditches, reversing the superelevation, and widening the roadway on a few select curves. These modifications were estimated to cost $300 per station for half of the length of the link (Table 1). We assumed that only half of the segment length needed to be modified because on a forest road (using a conservative estimate) curves are approximately half of the transportation network.

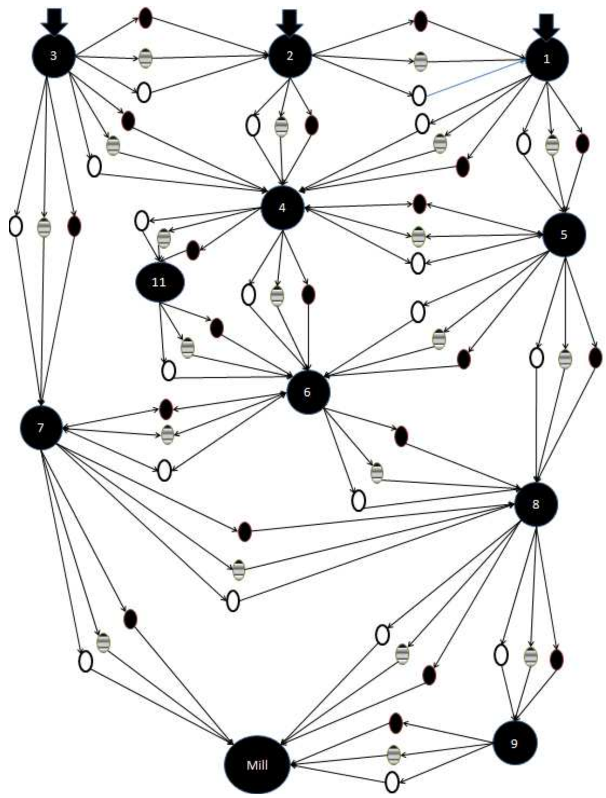


Figure 1. Small example road modification network, adapted from (Sessions 1985).

The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 53-ft drop center 5th-wheel chip van, small horizontally hatched circles indicate the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van.

Table 1. Chip Van Operating Characteristics.

Trailers	Volume Capacity cubic feet	Stations per Hour on Forest Roads	Stations per Hour on Highways	Operating Cost $/hr	Modification Cost $/Station
42' Stinger	2,600	528	2,376	$95.37	$0
45' Drop Center 5th-wheel	3,300	528	2,376	$90.95	$100
53' Drop Center 5th-wheel	4,000	528	2,376	$99.79	$300

The sale nodes for the small network are nodes 1, 2, and 3. The associated amount of biomass for each sale (chips or hogfuel) is identified in Table 2. All of the biomass is to be delivered to only one Mill (Node 10). The haul and modification costs per link are provided in the appendix (Table 5).

Table 2. Sale Nodes

Volume of Biomass		
Harvest Node	**Destination Node**	**Biomass (million ft^3)**
1	10	4.8
2	10	1.02
3	10	6.2

The ACO had a stopping criterion of 1,000 iterations. The heuristic converged on its solution rather quickly (iteration 282). The optimal solution to this problem using the ACO is $72,139.50. This amounted to $6,225 in modification costs and $65,914.50 in hauling costs. The optimal path is shown for each sale in Table 3. There were 1,454 trips from Unit 1 to the Mill, 309 trips from Unit 2 to the Mill, from and 1,550 trips from Unit 3 to the Mill.

Table 3. The Optimal Path for the Small Network Using Ant Colony Heuristic.

Total Cost	$72,139.50	
Sale 1	**Sale 2**	**Sale 3**
Truck Type	**Truck Type**	**Truck Type**
45' Drop Center 5th-wheel	45' Drop Center 5th-wheel	53' Drop Center 5th-wheel
Best Node Path	**Best Node Path**	**Best Node Path**
1	2	3
5	4	7
6	11	10
7	6	
10	7	
	10	

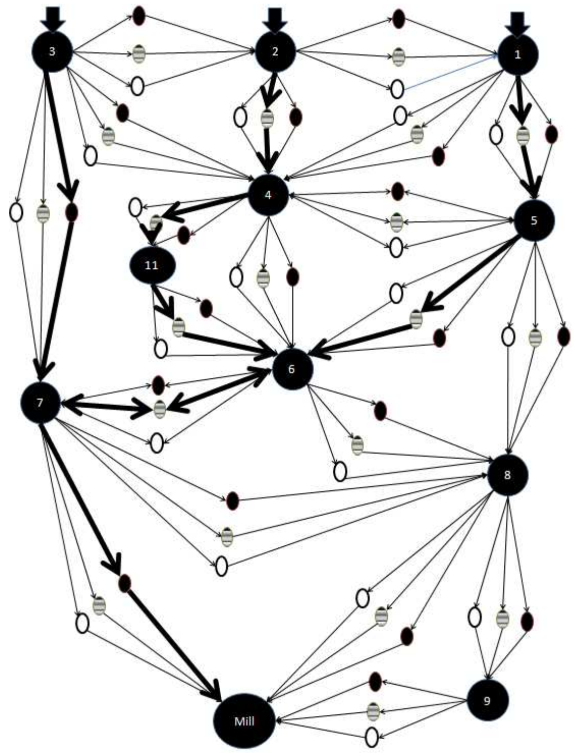


Figure 2. Ant Colony Optimal Haul Routes.

The bold arrows indicate optimal haul routes. The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 53-ft drop center 5th-wheel chip van, the small horizontally hatched circles indicate the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van.

The ACO solution was compared to a mixed integer solution. The mixed integer programming solution is found in Table 4 and Figure 3. The mixed integer and ACO produced similar results; a $13.46 difference between the two approaches. This was the result of rounding when formulating the mixed integer problem. Both methods used the same truck types and paths to transport the biomass to the mill. This small example illustrates that the heuristic appears reasonable for determining near optimal solutions for similar road modification problems.

Table 4. The Optimal Path for the Small Network Using Mixed Integer Programming.

Total Cost	$72,154.26	
Sale 1	**Sale 2**	**Sale 3**
Truck Type	**Truck Type**	**Truck Type**
45' Drop Center 5th-wheel	45' Drop Center 5th-wheel	53' Drop Center 5th-wheel
Best Node Path	**Best Node Path**	**Best Node Path**
1	2	3

5	4	7
6	11	10
7	6	
10	7	
	10	

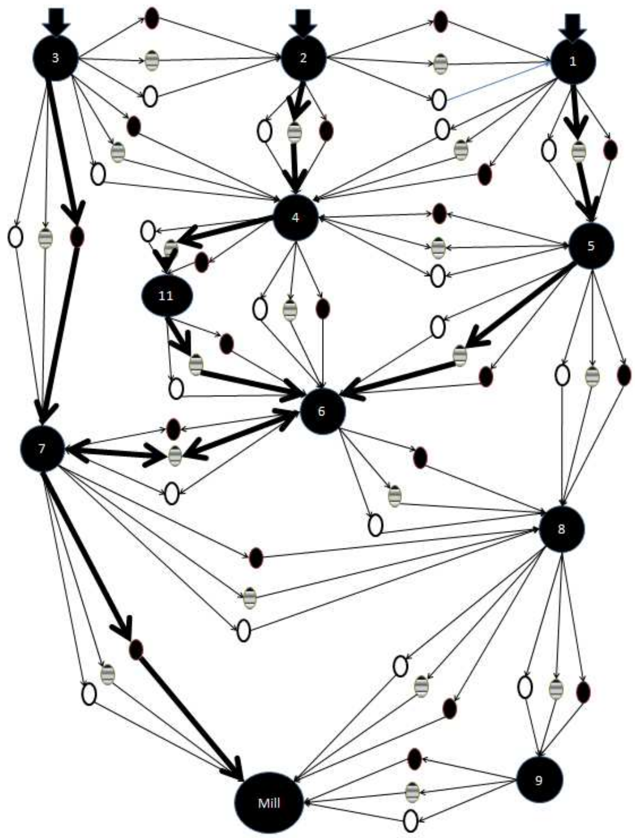


Figure 3. Mixed Integer Optimal Haul Routes.

The bold arrows indicate optimal haul routes. The large black circles indicate nodes within the transportation network. The small black circles indicate the road modification option for the 53-ft drop center 5th-wheel chip van, small horizontally hatched circles indicate the road modification option for the 45-ft drop center 5th-wheel chip van, and the small white circles indicate the road modification option for the stinger-steered chip van.

Application to a realistic forest transportation network

Following the favorable results of the small network, the ACO heuristic was used on the McDonald Forest, to determine the least cost path for future harvesting activities. McDonald Forest is located seven miles north of Corvallis and is managed by Research Forest staff, College of Forestry, Oregon State University. McDonald Forest is a teaching, research and demonstration forest revolving around four themes. These themes are 1) Short Rotation Wood Production with High Return on Investment, 2) High

Quality, Growth Maximizing Timber Production, 3) Visually Sensitive, Even-aged Forest, and 4) Structurally Diverse Forest (Fletcher, et al., 2005).

Biomass utilization is gaining interest in western Oregon and several biomass-powered cogeneration plants exist within 60 miles of McDonald Forest. A major cost of biomass operations is the transportation cost and with small profit margins, thus it is important to determine the least cost method for transporting biomass from the woods to the mill. Being able to determine the optimal trucks and haul routes that would reduce total transportation costs would be important to the decision to utilize biomass. We applied the ACO heuristic to develop a least cost path from a sample of harvest units distributed through McDonald Forest. McDonald Forest is approximately 7,200 acres with 70 miles of road or about 6 miles of forest roads per square mile (Lysne and Klumph, 2011). The McDonald Forest road network and possible truck routes through Corvallis are shown in Figure 3.

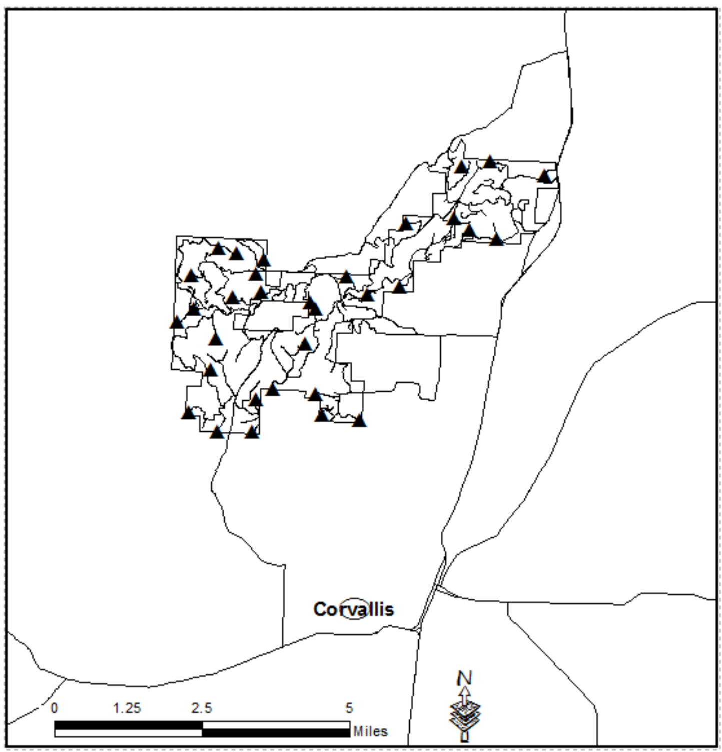


Figure 4. McDonald Forest Road Network, Corvallis, Oregon. The black triangles are the sale nodes.

Thirty hypothetical timber harvests (sales) were spread through McDonald Forest (Figure 3) for the purpose of reducing fuel loading around the urban interface. These timber harvests were assumed to produce and recover 40 green tons of biomass per acre or 4,000 ft^3 of biomass with about 50 percent moisture content. It was estimated that each sale would harvest between 120 and 240 acres (black triangles in Figure 3). The destination node for all of the transported biomass is a biomass plant in Eugene (30 miles south of Corvallis). The estimated travel speed on forest roads was 10 mph and

45 mph on major highways. On public highways, it was assumed that any truck combination could be used without incurring any road modification costs.

The transportation network included 405 nodes and 2,433 links, including the existing transportation network and two modification options for each link. The existing transportation network was assumed to only permit stinger-steered trailer access. The other two trailer types required temporary road modification for access similar to the small network problem. The chip van operating characteristics in this problem are the same as Table 1. Once the chip vans were outside of the McDonald Forest, it was assumed that any chip van could be used without incurring a road modification cost. It was also assumed that adequate turnarounds exist to permit use of each truck type.

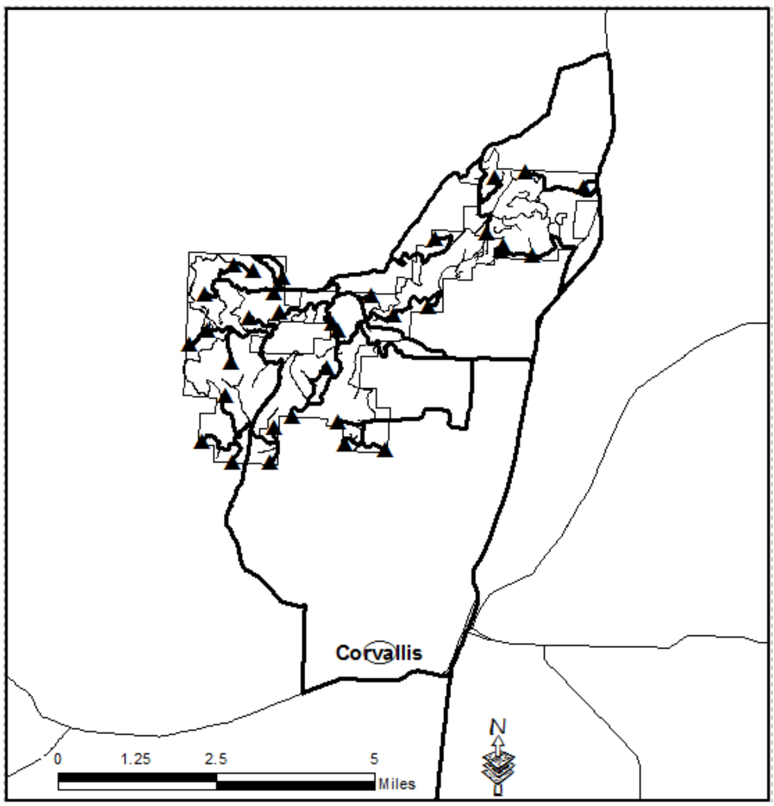


Figure 5. Optimal route path for all 30 sales, McDonald Forest, Corvallis, Oregon.

The bold routes are the optimal paths. The black triangles are the sale nodes.
The optimal routes for the 30 sales are shown in Figure 5. For 29 sales, the ACO determined the least cost path used a 53-ft drop center 5th-wheel chip van and for one sale, a 45-ft drop center 5th-wheel chip van was chosen. The total transportation cost was $1,491,020 with $219,820 in road modification costs and $1,271,200 in haul costs. The road modification costs amount to fifteen percent of the total cost. If no road modifications had been made, only the stinger steered chip van could have been used with a total transportation cost of $1,815,650 (100 percent haul costs). In this example, the ability to modify the roadway to allow larger trucks access to these sales reduced the total transportation cost by 22 percent. The ability to reduce transportation costs by 22 percent is a large benefit when margins are as slim as they are in the biomass

market. This implies that being able to reduce the haul cost with the application of road modifications could have a significant positive impact.

Concluding Comments

The ACO heuristic obtained an optimal solution to a small problem and when applied to a more realistic problem provided a solution quickly. As the amount of volume being transported increases, the more a company could spend on road modifications to allow larger truck capacity access. Being able to change the forest transportation network to allow larger truck access could dramatically reduce hauling costs. Further research is required to determine if the associated costs used in this paper accurately represent the road modification costs required to allow these non-standard trucks access. Further research is also required to determine the effect of superelevation has on the magnitude of non-standard truck off-tracking on forest roads.

Literature Cited

Beathe, J. 2011. Starker Forests' Road Inventory. Beck, S. Interviewer. Corvallis, Oregon.

Contreras, M. A., Chung, W., and Jones, G. 2008. Applying Ant Colony Optimization Metaheuristic to Solve Forest Transportation Planning Problems with Side Constraints. Canadian Journal of Forest Research, 38, 2896-2910.

Craven, M., Wing, M., Session, J., and Wimer, J. 2011. Assessment of Airborne Light Detection and Ranging (LiDAR) for use in Common Forest Engineering Geomatic Applications. M.S. Thesis, Oregon State Universtiy, College of Forestry, Corvallis. Retrieved from Oregon State University: http://hdl.handle.net/1957/21803

Donati, A. V., Montemanni, R., Casagrande, N., Rizzoli, A. E., and Gambardella, L. M. 2008. Time Dependent Vehicle Routing Problem with a Multi Ant Colony System. European Journal of Operational Research, 185, 1174-1191.

Fletcher, R., Johnson, B., Blanchard, G., Hayes, J., Johnson, N., Johnson, D., Lysne, D., Murphy, G., Newton, M.; Sessions, J. 2005. McDonald-Dunn Forest Plan. Last Accessed May 5, 2012, from http://www.cof.orst.edu/cf/forests/mcdonald/plan/files/mcdunn_plan.pdf

Lysne, D., and Klumph, B. 2011. OSU College Forests' Road Inventory. Beck, S. Interviewer. Corvallis, Oregon.

Rizzoli, A. E., Montemanni, R., Lucibello, E., and Gambardella, L. M. 2007. Ant colony Optimization for Real-World Vehicle Routing Problems: From Theory to Applications. Swarm Intelligence, 1, 135-151.

Sessions, J. 1985. A Heuristic Algorithm for the Solution of the Variable and Fixed Cost Transportation Problem. Society of American Foresters Symposium p. 324-336. Athens, Georgia: Georgia Center for Continuing Education.

Sessions, J., Wimer, J., Costales, F., and Wing, M. G. 2010. Engineering Considerations in Road Assessment for Biomass Operations in Steep Terrain. Western Journal of Applied Forestry, 25(3), 144-153.

Table 5. Haul and Modification Cost for the Small Network

Link Identifier		**Truck Type**	**Round Trip Haul Cost $/Truck/Link**	**Modification Cost $/Link**
From	**To**			
1	4	42' Stinger	18.79	0
1	4	45' Drop Center 5th-wheel	17.91	2,600.00
1	4	53' Drop Center 5th-wheel	19.66	7,800.00
1	5	42' Stinger	6.14	0
1	5	45' Drop Center 5th-wheel	5.86	850
1	5	53' Drop Center 5th-wheel	6.43	2,550.00
2	1	42' Stinger	12.28	0
2	1	45' Drop Center 5th-wheel	11.71	1,700.00
2	1	53' Drop Center 5th-wheel	12.85	5,100.00
2	4	42' Stinger	6.14	0
2	4	45' Drop Center 5th-wheel	5.86	850
2	4	53' Drop Center 5th-wheel	6.43	2,550.00
3	2	42' Stinger	9.39	0
3	2	45' Drop Center 5th-wheel	8.96	1,300.00
3	2	53' Drop Center 5th-wheel	9.83	3,900.00
3	4	42' Stinger	6.5	0
3	4	45' Drop Center 5th-wheel	6.2	900
3	4	53' Drop Center 5th-wheel	6.8	2,700.00
3	7	42' Stinger	6.32	0
3	7	45' Drop Center 5th-wheel	6.03	875
3	7	53' Drop Center 5th-wheel	6.61	2,625.00
4	5	42' Stinger	9.03	0
4	5	45' Drop Center 5th-wheel	8.61	1,250.00
4	5	53' Drop Center 5th-wheel	9.45	3,750.00
4	6	42' Stinger	6.14	0
4	6	45' Drop Center 5th-wheel	5.86	850
4	6	53' Drop Center 5th-wheel	6.43	2,550.00
4	11	42' Stinger	4.34	0
4	11	45' Drop Center 5th-wheel	4.13	600
4	11	53' Drop Center 5th-wheel	4.54	1,800.00
5	4	42' Stinger	7.95	0
5	4	45' Drop Center 5th-wheel	7.58	1,100.00
5	4	53' Drop Center 5th-wheel	8.32	3,300.00
5	6	42' Stinger	3.61	0

Link Identifier		Truck Type	Round Trip Haul Cost $/Truck/Link	Modification Cost $/Link
From	To			
5	6	45' Drop Center 5th-wheel	3.45	500
5	6	53' Drop Center 5th-wheel	3.78	1,500.00
5	8	42' Stinger	6.14	0
5	8	45' Drop Center 5th-wheel	5.86	850
5	8	53' Drop Center 5th-wheel	6.43	2,550.00
6	7	42' Stinger	5.42	0
6	7	45' Drop Center 5th-wheel	5.17	750
6	7	53' Drop Center 5th-wheel	5.67	2,250.00
6	8	42' Stinger	6.5	0
6	8	45' Drop Center 5th-wheel	6.2	900
6	8	53' Drop Center 5th-wheel	6.8	2,700.00
7	6	42' Stinger	1.81	0
7	6	45' Drop Center 5th-wheel	1.72	250
7	6	53' Drop Center 5th-wheel	1.89	750
7	8	42' Stinger	6.5	0
7	8	45' Drop Center 5th-wheel	6.2	900
7	8	53' Drop Center 5th-wheel	6.8	2,700.00
7	10	42' Stinger	9.03	0
7	10	45' Drop Center 5th-wheel	8.61	0
7	10	53' Drop Center 5th-wheel	9.45	0
8	9	42' Stinger	5.06	0
8	9	45' Drop Center 5th-wheel	4.82	700
8	9	53' Drop Center 5th-wheel	5.29	2,100.00
8	10	42' Stinger	19.51	0
8	10	45' Drop Center 5th-wheel	18.6	0
8	10	53' Drop Center 5th-wheel	20.41	0
9	10	42' Stinger	9.03	0
9	10	45' Drop Center 5th-wheel	8.61	0
9	10	53' Drop Center 5th-wheel	9.45	0
11	6	42' Stinger	0.36	0
11	6	45' Drop Center 5th-wheel	0.34	50
11	6	53' Drop Center 5th-wheel	0.38	150

Early Commercial Thinning in Maine's Spruce-Fir Forests

Jeffrey G. Benjamin[1], Emily Meacham, Robert Seymour and Jeremy Wilson

Abstract

Many of Maine's regenerating clearcuts from the spruce budworm outbreak of the 1980s are dominated by dense spruce and fir saplings with a small component of hardwood. Some of these stands were pre-commercially thinned; others, however, have grown beyond the stage where brush-saw treatment is feasible. Such stands are overstocked and would benefit from thinning, but they are many years away from being operable with traditional harvesting systems and there is no consensus within the industry as to how these young stands should be treated. This study allowed three sectors of the forest industry (landowners, contractors, and equipment dealers & manufacturers) to investigate silviculturally effective, operational solutions to implement early commercial thinning treatments. During the summer of 2011, three new harvesting machines (Ponsse Fox, John Deere 1170E, and CAT 501 tracked feller buncher) were compared to a John Deere 753J swing-to-tree feller buncher. Comparisons between the whole-tree and cut-to-length systems were made in terms of residual stem damage, product utilization, and unit cost of production. Results indicate that there was a difference in wound area (high severity rating) between harvest methods (p=0.007) and significantly more crops trees were removed (p=0.030) from the whole-tree operations. Round wood production was the same for CTL and WT (average 67.2 tonne/ha (30 ton/ac)), but over four times more biomass was produced from the whole-tree operations (37.7 tonne/ha (16.8 ton/ac)). Production costs were not significantly different between harvest method due in part to high machine productivity and increased biomass production for the whole-tree systems.

Introduction

Many of Maine's regenerating clearcuts from the spruce budworm era are dominated by dense spruce and fir saplings (< 15 cm. (6 in.) dbh) with a small component of hardwood. Some of these stands were pre-commercially thinned; others, however, have grown beyond the stage where brush-saw treatment is feasible. Such stands are overstocked and would benefit from thinning, but they are decades away from being operable with traditional harvesting systems. The Maine Forest Service (2008) estimates that thinning these overstocked stands could provide an additional 1.4 million green tons of wood annually. Unfortunately, there is no consensus within the industry as to how these young stands should be treated. Landowners feel stand growth will be improved with early commercial thinning and that the economic value of the harvested material should be adequate to cover harvest costs. Local equipment

[1] Associate Professor of Forest Operations, University of Maine, Orono ME

dealers/manufacturers are eager to test specialized equipment that is commercially available for both harvesting and transporting small-diameter material to roadside. Contractors, however, are unsure if they can economically harvest these stands since their current mix of equipment was not designed to handle and process small-diameter stems. Further, given current market realities, contractors are reluctant to invest heavily in specialized equipment.

The Cooperative Forestry Research Unit (CFRU) at the University of Maine is monitoring growth response to commercial thinning trials across a variety of sites as part of the Commercial Thinning Research Network. These trials were implemented on older sites where most stems had already reached commercial size and the treatments were designed for cut-to-length systems and only round wood products. Given the presence of an active regional energy wood market, and because over 80 percent of the volume harvested in Maine is by whole-tree systems (Benjamin and Leahy 2011), it is important to consider such commercial thinning treatments from a different perspective. In 2010, the CFRU funded a project that allowed three sectors of the forest industry (landowners, contractors, and equipment dealers/manufacturers) to assess silviculturally effective operational solutions for implementing early commercial thinning (ECT) treatments. This paper will present results from that study focused on a comparison of whole-tree and cut-to-length systems in terms of residual stand damage, product utilization, and unit cost of production.

Methods

Study Site Description

The 9.7 ha (24 ac) research site is located in central Maine, approximately 40 km (25 miles) from the University of Maine, on forestland managed by American Forest Management. The site regenerated from a clearcut in the early 1970s and approximately 8.1 ha (20 ac) was pre-commercially thinned ca. 1985[2]. Species composition of the site consisted of *Abies balsamea* (balsam fir) (59%), *Pinus strobus* (eastern white pine) (24%), *Picea rubens* (red spruce) (12%) and a variety of other species (5%) including *Acer rubrum* (red maple), *Tsuga canadensis* (eastern hemlock), *Fagus grandilifolia* (American beech), *Populus tremuloides* (quaking aspen), *Prunus pensylvanica* (pin cherry), and *Betula papyrifera-,populifolia-,* and *allegheniensis* (paper-, grey-, and yellow- birch). Roughly half of the site was on moderately well drained soil that consisted of a very stony loam, and the other half was on somewhat poorly drained soil that consisted of a very stony silt loam.

Equipment Selection and Harvest Plan

Twenty-two research plots were established along trails spaced either 15.2 m (50 ft) or 24.4 m (80 ft) from trail-center to trail-center. All plots were 0.08 ha (0.2 ac) in size, but plot length varied by trail spacing. Equipment was selected for this study in consultation

[2] This paper will only present results from the PCT portion of the study. Demonstration harvests were conducted in the non-PCT stand (four acres), but ground conditions prevented replication of harvest activity.

and cooperation with local equipment dealers and one of the land manager's preferred logging contractors. As indicated in Table 1, two new CTL processors and a new tracked feller buncher were compared to a larger feller buncher common to the industry. The primary focus of this study was the performance of harvesting equipment in a thinning context, but productivity and cost of the full operation was also considered, so primary transportation and roadside processing were included. Forwarding was conducted using a Ponsse Wisent and a Valmet 644. All skidding and roadside processing was conducted using a JD 648GII grapple skidder and a JD 200LC stroke delimber.

Table 1. General specifications of harvesting equipment used in this study.

Harvest Method	Machine	Specifications Width m (ft)	Weight tonne (lbs)	Reach m (ft)	Clearance m (in)	Gross Power @ 2000 kw (hp)
CTL	John Deere 1070E	2.6 (8.5)	14.7 (32,400)	10.7 (35)	0.56 (22)	136 (182)
CTL	Ponsse Fox	2.7 (9.0)	17.7 (39,000)	10.0 (33)	0.61 (26)	147 (197)
WT	CAT 501	2.6 (8.5)	15.9 (35,000)	7.0 (23)	0.66 (24)	157 (157)
WT	John Deere 753J	3.2 (10.5)	23.6 (52,000)	8.2 (27)	0.74 (29)	164 (220)

The machine operators had varying degrees of experience with the harvesting equipment. The CTL operators each had over 20 years of experience; one was an operator trainer for John Deere and the other had operated several Ponsse processors for local logging companies. The operator for the CAT 501 was retired from the logging industry, but he had over 30 years of experience operating whole-tree harvesting equipment. The operator for the second feller buncher (753J) only had five years of experience, but he operated that machine for over 11,000 hours and was considered proficient for the study. The operators for the skidding and roadside processing equipment each had over 30 years of experience and thousands of operating hours on the machines used in this study. Prior to the research harvest, each operator was given the opportunity to harvest in a practice area near the research site to ensure familiarity with specific machine functions.

Based on a pre-harvest inventory and results from the CTRN, target basal area removal was 50% plus trails. The harvest was expected to shift species composition to eastern white pine and red spruce as well as favor higher quality stems by removing:

- all old residual stems greater than 30 cm dbh (12 in) from previous harvest
- all hardwoods
- all poorly formed eastern white pine
- all trees within machine trails;
- all balsam fir greater than or equal to 21.6 cm dbh (8.5 in); and

- remaining balsam fir and intolerant hardwoods as necessary to achieve 50% removal.

Operationally, the prescription favored eastern white pine spaced at 4.6-6.1 m (15-20 ft) and red spruce at 3.0-3.7 m (10-12 ft). Trees were painted for removal in the research plots only, so that machine operators harvested the remainder of each trail with no further guidance.

Active Harvest Measurements

Plot-level and trail-level production data were collected during active operations. At the plot-level, individual machine cycle times were recorded with respect to dbh (5 cm (2 in) classes corresponding to colors of marked stems) and species using a time study program (LAUBRASS inc., UMT plus V. 16.7.14) installed on a PDA handheld device (Palm Tungsten E2). A feller buncher cycle began and ended with empty accumulators at the bunch and included the time to harvest, accumulate, and place a bunch in a twitch. Time within each cycle was also noted for trail work, removal of snags or non-merchantable stems, re-piling a twitch, and excessive travel. A processor cycle began and ended with a saw cut and included the time to fell, delimb, top, process, and select the next stem. If multi-stem processing occurred, the cycle ended after all stems were processed and a new stem was selected with empty accumulators. Time within each cycle was also noted for any trail work, removal of snags or non-merchantable stems, processing rot, excessive work to delimb forks, and excessive travel.

At the trail-level, total productive machine hours were recorded for each machine using a combination of manual stopwatches and the PDA system described above. Round wood and biomass volume was estimated at roadside and cross referenced with mill scale records provided by the logging contractor. Fuel consumption rates for each machine were calculated based on overall fuel usage for each machine during the operations. Standard machine rate assumptions and calculations, as outlined in Brinker *et al.* (2002), were used to develop hourly machine rates for each piece of logging equipment (Table 2). Data were obtained through personal communication with equipment dealers and logging contractors participating in this study[3].

Table 2. Data and assumptions used to develop machine rates.

Item	Value or Range	Units
Machine Life	5	years
Scheduled Machine Hours	2200-2400	hours
Utilization Rate	75-85	%
Salvage Value	20	%
Interest Rate	4-5	%
Fuel Price	4	$/gal
Fuel Consumption Rate	0.015-0.044	gal hp^{-1} hr^{-1}
Operator Wage	11-18	$/hr
Operator Benefit Rate	40	%

[3] Quotes for purchase price on each piece of equipment were obtained from equipment dealers to develop machine rates, but cannot be shared in this publication.

Post-Harvest Measurements

A 100% tally in each plot was completed post-harvest for all standing residual trees greater than or equal to 5 cm dbh (2.0 in). Data recorded included dbh, height of every 10th tree and species. Each residual tree was thoroughly inspected for damage related to the recent harvesting activities. Causes of damage were not differentiated between harvesting and skidding activities. Stems that were completely bent over or uprooted were not included in the final residual stem count. Damage was assessed using the Ostrofsky et al. (1986) method where wounds were recorded as injured or uninjured and classified by severity. For each wound, width perpendicular to stem and length parallel to them stem at the widest and longest points were recorded as well as wound location in terms of height from the ground. Severity was categorized within 3 classes: 1) Low; bark scuff, 2) Moderate; cambium broken with uninjured sapwood, 3) High; cambium broken with injured sapwood. When combinational wounds were found, severity class was assigned by the highest severity present. If wounds were low and discontinuous, they were classified as low and assigned an approximated percentage of wound cover. Each wound on a tree was assessed and recorded separately unless it could be assumed that the damaged area would eventually converge and were then measured as one continuous wound. Crown and root damage were noted when present.

Results

Stand Inventory

Descriptive statistics for pre- and post-harvest inventory can be found in Table 3 and Table 4 respectively. Error was assessed using a 95% confidence interval. Volume was approximated using Honer's volume equation which relies on heights estimated from a regression line of observed vs. predicted heights. Approximately 24 m^2/ha (105 ft^2/ac) of basal area was removed, including machine trails. Total basal area removal came out to be just over 60%. Close to 1235 trees/ha (500 trees/ac) were removed in the harvest. The plots were marked with no bias towards machine trails. Regardless of trail area, the removal was heavier than expected. This may be due to operational effects or because of the low number of quality residuals to choose from when marking the pre-harvest stand. The post-harvest results in Table 4 include machine trail area.

Table 3. Pre-harvest assessment of PCT stand.

Statistic	Volume m^3/ha (ft^3/ac)	BA m^2/ha (ft^2/ac)	Trees per Area ha (ac)	QMD cm (in)
Mean	271.0 (3871.3)	38.8 (168.8)	1801 (729)	16.8 (6.6)
SD	41.2 (588.7)	5.1 (22.0)	279 (113)	1.27 (0.5)
CV	15%	13%	16%	8%
SE	9.2 (131.6)	1.1 (4.9)	62.5 (25.3)	0.25 (0.1)
%SE	3%	3%	3%	2%

Table 4. Post-harvest assessment of PCT stand.

Statistic	Volume m^3/ha (ft^3/ac)	BA m^2/ha (ft^2/ac)	Trees per Area ha (ac)	QMD cm (in)
Mean	109.7 (1566.6)	15.3 (66.5)	598 (242)	18.0 (7.1)
SD	25.4 (362.2)	3.2 (13.9)	91 (37)	1.5 (0.6)
CV	23%	21%	15%	9%
SE	5.7 (81.0)	0.7 (3.1)	20.2 (8.2)	0.25 (0.1)
%SE	5%	5%	3%	2%

Residual Stand Damage

Ostrofsky and Dirkman (1991) considered moderate and high severity wounds on residual stems to be the most likely to cause volume and value loss over time. Table 5 summarizes the average percentage of individual stems per plot damaged with either high or moderate severity by harvest method and trail spacing. There was significantly more stems wounded in total by the CTL method (31%) compared to the WT method (20%) ($p=0.006$), but there was no difference in the number of stems with high severity wounds ($p=0.808$). There were no differences in number of stems wounded between harvest method and trail spacing.

Table 5. Average percentage of trees per plot with significant damage, including moderate and high severity.

Severity Rating	Cut-to-Length		Whole-Tree	
	15.2 m (50 ft)	24.4 m (80 ft)	15.2 m (50 ft)	24.4 m (80 ft)
High	6%	5%	5%	5%
Moderate	28%	25%	16%	14%
Total	34%	30%	21%	19%

Total wound area by severity level can be found in Figure 1 for each harvest method and trail spacing. There was no statistical difference in moderate and high wound area at the plot level between CTL and WT methods ($p=0.637$). The WT method, however, did have more wound area (0.30 m^2 (3.2 ft^2)) per plot in the high severity class than the CTL method (0.14 m^2 (1.5 ft^2)) ($p=0.011$). Wound area per tree was also greater for the WT method (0.04 m^2 (0.43 ft^2)) compared to the CTL method (0.02 m^2 (0.24 ft^2)) ($p<0.001$). There were no differences in wound area at the plot- or tree-level with respect to trail spacing.

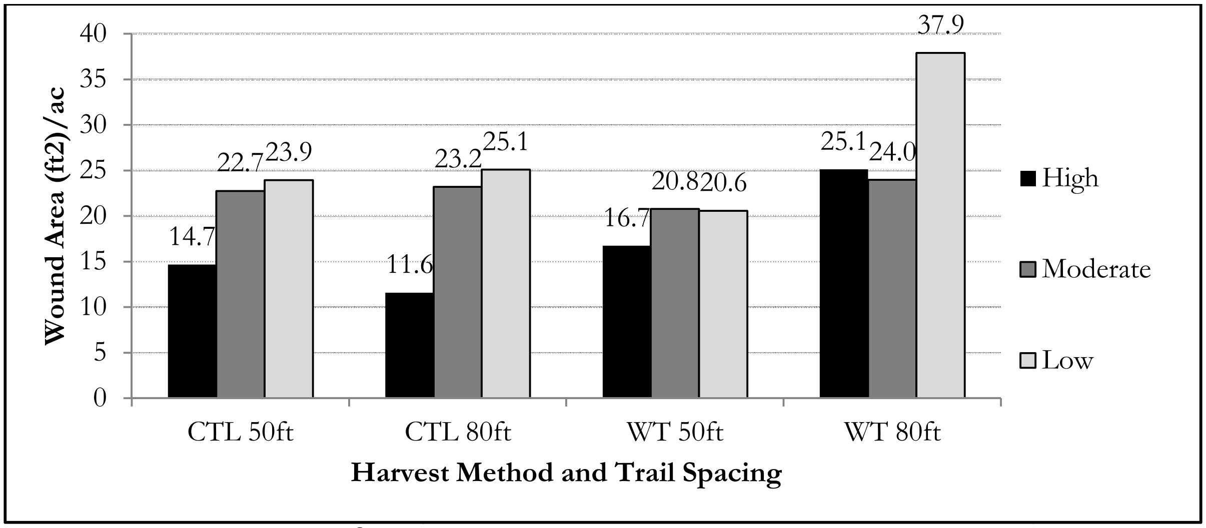


Figure 1. Wound area (ft^2/ac) separated by severity class and shown by harvest method and trail spacing.

Arguably the most important form of stand damage is that of crop tree loss by trail access or machines reaching into treatment zones. As shown in Figure 2 crop tree loss by both harvest methods was substantial regardless of trail spacing. With the exception of CTL at 24.4 m (80 ft), crop tree loss was between 17% and 25%. There was significantly more crop tree loss from WT systems (22%) compared to CTL systems (12%) ($p=0.023$) and on trails spaced 15.2 m (50 ft) apart (21%) compared to 24.4 m (80 ft) apart (14%) ($p=0.098$).

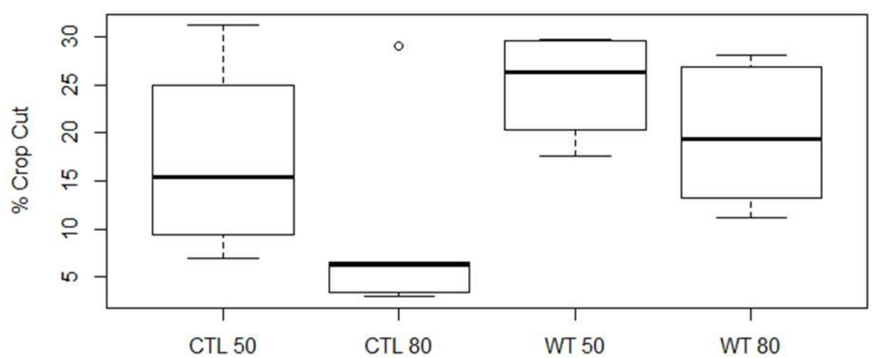


Figure 2. Percent of crop tree loss, with respect to basal area, by harvest method and trail spacing.

Product Utilization

One of the objectives of this study was to determine the amount of woody biomass that could be harvested from the stand with each harvest system. Operators were instructed to leave tops, limbs, and other logging residue in the trails as necessary to reduce compaction and erosion, but all other woody biomass was to be harvested and transported to roadside. As the same harvest prescription was applied across the site, it is not surprising that both CTL and WT systems produced the same amount of round wood at 71.5 tonne/ha (31.9 ton/ac) and 63.0 tonne/ha (28.1 ton/ac) respectively. With respect to woody biomass, the WT systems produced four times more than the CTL systems (37.7 tonne/ha (16.8 ton/ac) and 9.4 tonne/ha (4.2 ton/ac)). This resulted in a total production of 100.7 tonne/ha (44.9 ton/ac) and 80.9 tonne/ha (36.1 ton/ac) for WT and CTL systems respectively as shown in Figure 3.

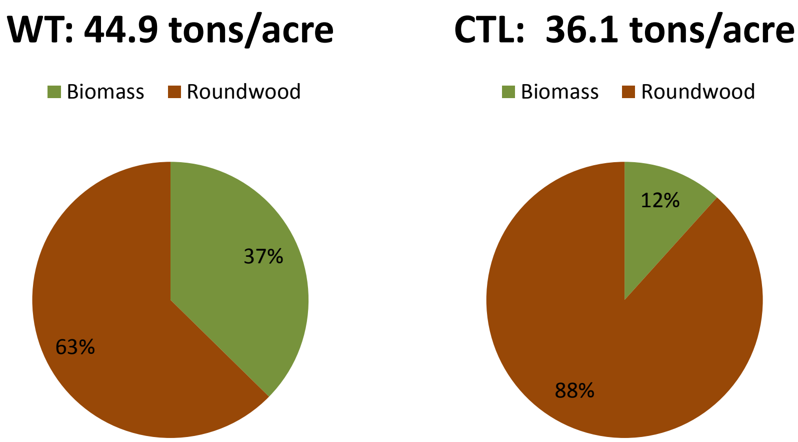


Figure 3. Product utilization in percent round wood and biomass by harvest method.

Unit Cost of Production

Feller bunchers are expected to harvest significantly more stems per hour than processors given that processors complete more work functions in a cycle. As shown on Figure 4, the feller bunchers from this study more than doubled the production (18.7 tons/pmh to 7.61 tons/pmh) of the processors (p=0.005). In order to compare production costs, however, the entire system must be considered. Time and motion studies conducted on transportation and roadside processing equipment were used to scale production estimates to typical operating conditions. For example, the maximum skidding distance on the site was approximately 150 m (500 ft), but it was scaled to an industry average of 300 m (1000 ft)[4]. Productivity estimates per machine were combined with machine rates (Table 6) to develop system level cost estimates. As shown on Figure 5, there is no statistical difference in production costs between WT (32 $/ton) and CTL (32 $/ton) systems (p=0.990), but there is a high degree of variability within the CTL system costs, which is evident on Figure 6.

[4] Personal communication with several local contractors indicated that skidding distances greater than 2000 ft. would result in negotiated rate increases with landowners. Although contractors routinely transport wood up to 1500 ft., it was assumed for this study to use 1000 ft. as an industry average.

Table 6. Machine rate ranges used in system-level cost estimates.

Harvest Method	Machine	Rate Range ($/PMH)
Cut-to-Length	Processor: Ponsse Fox	118-153
	Processor: John Deere 1170E	124-161
	Forwarder: Ponsse Wisent	92-118
Whole-Tree	Feller Buncher: CAT 501	103-131
	Feller Buncher: JD 753J	116-143
	Grapple Skidder: JD 648 GII	92-113
	Stroke Delimber: JD 200LC	115-147

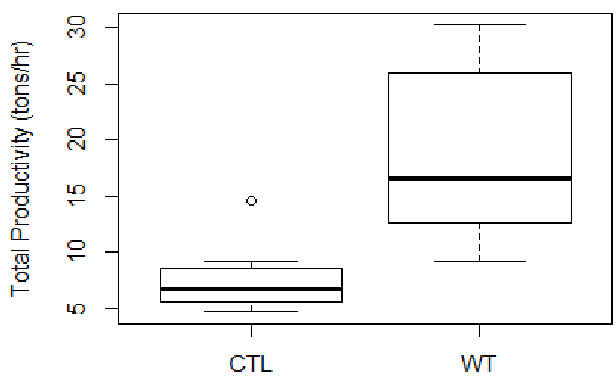


Figure 4. Variation in machine-level productivity (tons/hr) for feller bunchers (WT) and processors (CTL). Bold lines represent median productivity.

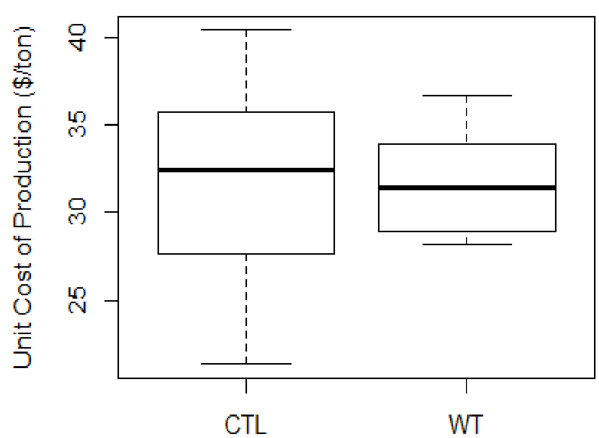


Figure 5. Variation in unit cost of production ($/ton) for WT and CTL systems. Bold lines represent median unit costs.

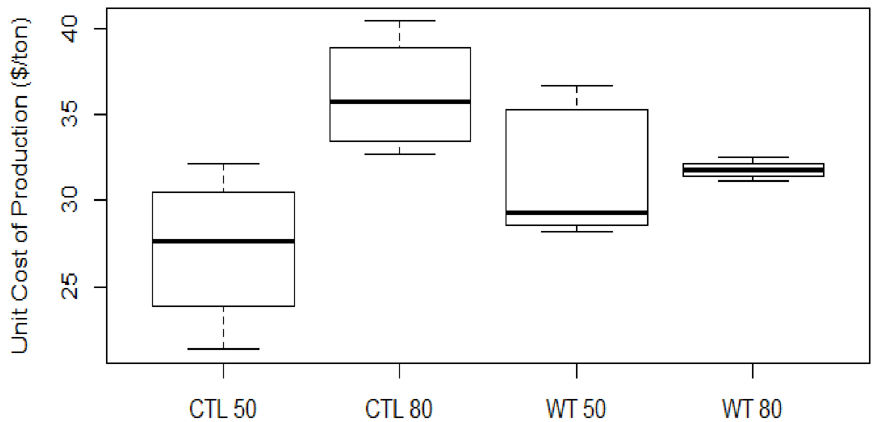


Figure 6. Variation in unit cost of production ($/ton) for WT and CTL systems by trail spacing.
Bold lines represent median unit costs.

Discussion and Conclusions

This study allowed landowners, contractors, and equipment dealers and manufacturers to assess silviculturally effective operational solutions for implementing early commercial thinning treatments. From a silvicultural perspective it is clear that we have commercially available equipment that can conduct such treatments. The CTL system at 80 ft. spacing (Figure 2) was able to achieve less than 10% crop tree loss on average. Unfortunately, there are still high amounts of residual stand damage across all systems and trail spacings and more importantly the best system silviculturally was also the most expensive (Figure 6). Given the additional reach and maneuverability of the dangle head processors (Table 1), it is surprising that the amount of wound area in the moderate and high severity classes is the same between harvest systems. There was more high severity damage from the WT system – presumably resulting from the skidding operations - but the overall damage is concentrated on fewer stems compared to the CTL system. Although some variability in stand damage was expected because of multiple equipment operators, the results clearly indicate systems harvest selection is a trade-off for the forester when designing a harvest plan and assessing post-harvest results.

From an equipment dealer perspective, it is encouraging to know that existing technology can conduct such treatments, but that optimism must be tempered with the realization that it takes skilled operators to ensure success. For example, a qualitative assessment of CTL operator performance indicated that it was the “finesse” operator who harvested the fewest crop trees and produced the least residual stem damage. The “production” operator was more cost effective, but had noticeably more stand damage. It is also important to note that even under optimistic scenarios, the unit costs to deliver this material roadside are still prohibitive under current market conditions.

There is a need for equipment manufacturers to continue efforts in development of harvesting machines that can cost effectively treat such stands.

No matter what the foresters and landowners would like to achieve with a harvest and no matter what the equipment dealers promise with respect to machine specifications and operating cost, it is the logging contractors that carry the biggest responsibility for the success of the operation. They need to balance the residual stand damage and crop tree selection with production costs. This study showed mixed results in terms of residual stand damage, but it will be years before the impact of observed damage on value and growth will be known. Of more immediate concern is the high unit cost of production. Under current market conditions with delivered biomass and pulp wood prices of $25/ton and $50/ton respectively, after road side delivery of $32/ton (Figure 5) there simply is not enough money left for chipping, transportation, or stumpage. The logging contractors in this region, however, are highly innovative (Stone *et al.* 2011) and they will continue to find ways to increase productivity and reduce operating costs to ensure such treatments will be feasible in the future.

Acknowledgements
In addition to the funding provided by the CFRU, this project would not have been possible without the commitment of many others including: American Forest Management, local equipment dealers and their respective manufacturers (Chadwick Ba-Ross & Ponsse, Nortrax & John Deere, Milton CAT & Caterpillar), local logging contractors (A.W. Madden, Randall Madden Trucking, Richard Adams Logging), and UMaine forestry students (Emily Meacham, Mallory Bussell, Molly Lizotte, Jacob Hicks, Jack Kelly).

References

Benjamin, J.G. and J.E. Leahy. 2011. Maine's Logging Contractor Survey – Preliminary Results. Forest Resources Association Northeast Region Industrial Forum: *Harvest Capacity – Is it Adequate to Meet Maine Forest Industry Needs?* Bangor, ME. October 6, 2011.

Brinker, R.W., J. Kinnard, B. Rummer, and B. Landford. 2002. Machine Rates for Selected Forest Harvesting Machines. Alabama Agriculture Experiment Station – Circular 296.

Maine Forest Service. 2008. Maine Forest Service Assessment of Sustainable Biomass Availability. www.maine.gov/doc/mfs/pubs/pdf/biomass_memo_071708.pdf. Accessed 02/18/10.

Stone, I.J., J.G. Benjamin, and J.E. Leahy. 2011. Applying Innovation Theory to Maine's Logging Industry. *Journal of Forestry.* 109(8):462-469.

Spatial modeling of potential woody biomass flow

Woodam Chung[1] and Nathaniel Anderson[2]

Abstract

The flow of woody biomass to end users is determined by economic factors, especially the amount of biomass available across a landscape and delivery costs of biomass to bioenergy facilities. The objective of this study is to develop a methodology to quantify landscape-level woody biomass stocks and potential biomass flows using the currently available spatial database and road network analysis tool. We applied this methodology to a study landscape of approximately 15 million acres around the city of Roseburg in southwestern Oregon. The analysis allows us to produce isocost contour maps that display the supply areas delineated by specific cost thresholds, as well as estimates of the amount of feedstock that can be delivered to specific sites on an annual basis for a specified haul cost. This methodology has the potential of providing useful information for determining the economically efficient scale and optimal location of a woody biomass utilization facility.

Keywords: woody biomass, biomass transportation, network analysis, spatial analysis

Introduction

Forest management activities, such as commercial harvests, fuel reduction thinning, and salvage operations, produce large quantities of forest residues. Interest in expanding the utilization of this biomass as a source of energy has increased significantly in recent years for a variety of reasons (Gan and Smith 2006, Jones et al. 2010). However, lack of information on realistic woody biomass supply and costs of feedstock has been a barrier to investment in woody biomass energy. Although many studies have estimated forest biomass stocks at a variety of scales based on FIA data (e.g., U.S. Department of Energy. 2011), a small body of research is devoted to developing biomass supply models that incorporate land management constraints, realistic treatment scenarios, forest operations research, transportation costs, and economic models of energy production. The objective of this study is to develop a methodology to 1) quantify landscape-level woody biomass stocks potentially available for energy production, and 2) model biomass flows using the currently available spatial database and road network analysis tool.

---

[1] Department of Forest Management, College of Forestry & Conservation, The University of Montana, Missoula, MT 59812, woodam.chung@umontana.edu

[2] Rocky Mountain Research Station, USDA Forest Service, Missoula, MT. nathanielmanderson@fs.fed.us

Methods

Study landscape

The study landscape is approximately 15 million acres located in Southwestern Oregon (Figure 1). The city of Roseburg, OR, is used as a potential location of a new biomass utilization facility for this study. Ownerships within the study landscape include private, USDA Forest Service, US Bureau of Land Management, USDA Forest Service Wilderness, National Park Service, etc. Forest cover in the study landscape was mapped using the Ecological Systems land cover dataset (ESFL) of 2008 in conjunction with the National Land Cover Dataset (NLCD 2001). The ESFL dataset includes 150 land cover classifications, which use the NLCD cover classification scheme. Of those, 47 are forest cover classes, including 4 deciduous forest classes, 33 evergreen forest classes, 5 mixed forest classes, 4 transitional forest classes, and one class for recently burned forest. Though species composition in each class varies, in general, forest classes are at least 10% canopy cover based on NLCD 2001. The state-wide coverage, detailed cover classifications, and relatively recent release date of this land cover model make it the best option for representing the forest area and forest types within the study landscape.

For this study, only forest designated as timberland based on both land cover and landownership is considered to be a source of biomass. Non-timber ownerships include all federal wilderness lands, National Park Service lands, State-owned scenic waterways and waysides, Fish and Wildlife Service lands, land owned by the Nature Conservancy (TNC), and many other categories. Though non-forest regions, including urban areas, can supply biomass in the form of wood waste and land clearing debris, in determining biomass flow for this study, land designated as non-forest is considered to provide zero biomass flow.

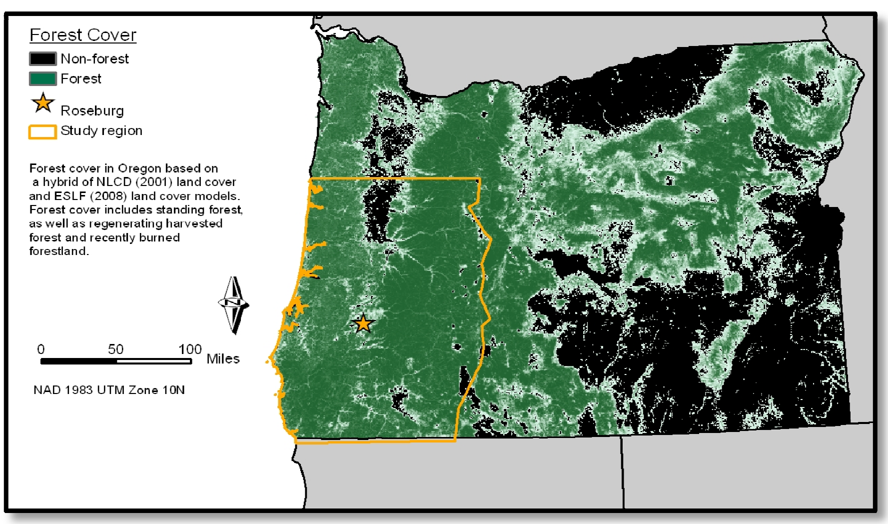


Figure 1. Study Landscape in Oregon.

Estimating the quantity of forest residues

The Timber Products Output (TPO) group of the Forest Inventory and Analysis Program (FIA) conducts periodic surveys of forest industry and other forest products producers and consumers to quantify flows of wood products throughout the country. TPO reports include data on removals of forest residues and roundwood, which includes sawlogs, veneer, pulpwood, fuel wood, and logs for posts and poles and composite wood products. For Oregon, TPO data is reported by county and splits removals into three ownership groups: National Forest, other public, and private. Residue and roundwood removals are reported in thousand cubic feet (mcf) for each ownership within each county. Data from 1996, 2001 and 2006 were used in this study to determine average annual removals of roundwood and residues per county and per ownership class. Conversion factors from USDA Forest Service (2007) and other sources were used to convert removals in mcf to bone dry tons (bdt), and then annual removals were normalized to bdt per acre of timberland. Non-timber forestland was not used in the calculation and is displayed as having zero product flow.

To estimate the quantity of residues potentially available for utilization, roundwood production was multiplied by a conversion factor of cubic feet of recoverable residues per mbf of roundwood harvest, with ratios determined by ownership class, geographic location and harvest type (Howard 1981). A map of the study landscape was then created with predicted recoverable residues in btd per acre of timberland per year for each of the ownership classes within each county. Available residues are finally determined by subtracting actual residue removals reported in TPO data from the predicted recoverable residues. The study landscape is rasterized into 30 x 30 meter grid cells, and each cell is then attributed with the amount of available residues per year per grid cell.

Modeling the flow of forest residues

Road network data for the study landscape were acquired from BLM - Oregon State Office. Spatial data errors included in the original data, such as disconnected links and loops, were detected and corrected. Road links were then built with from and to node pairs and attributed with design speed and distance for road network analysis. A round-trip travel cost in $ per bdt was calculated for each link. We assumed the average truck load and hourly cost to be 20 tons and $110, respectively.

Loading nodes for residue flow were placed along the existing roads with the minimum distance of 1 mile between two consecutive nodes. These loading nodes served as entry nodes for forest residues that are routed by truck to the final destination through the road network system. To estimate residue volume to be entered into each loading node, Thiessen polygons were created from each loading node. The annual amount of residues from each Thiessen polygon was then calculated by summing all biomass flow cells in the polygon. A road network analysis model was built using the road link data, loading nodes, entry volume for each loading node, and final destination location (i.e., Roseburg, OR). NETWORK2000 (Chung and Sessions 2003) was then used to identify the least cost route for each pair of entry and destination nodes.

Preliminary Results

The total amount of forest residues potentially available across the study landscape was estimated at approximately 2 million bdt per year. The amount of residues per acre widely varies with ownership classes ranging from 0 to 5 bdt. Figure 2 shows the total amount of residues in each Theissen polygon ranging from 0 up to over 5,000 bdt per polygon.

The results of NETWORK2000 runs present residue flows from each Thiessen polygon to the final destination with estimated transportation costs. Figure 3 shows estimated costs of residues originated from each Thiessen polygon. The costs widely varied with haul distance and road conditions, ranging from $15.24 to $80 per bdt.

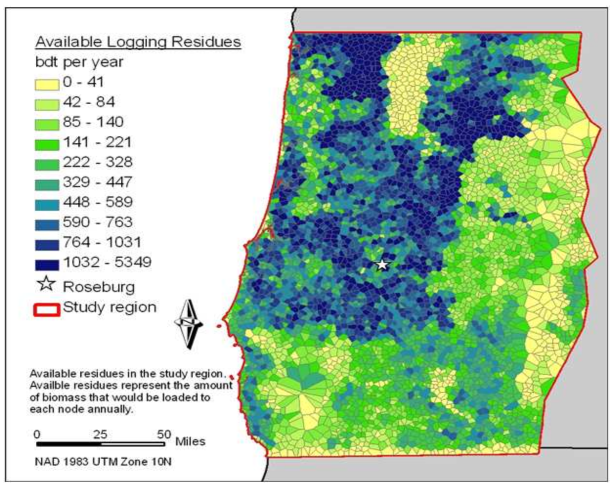


Figure 2. Annual amount of forest resides available in each Thiessen polygon.

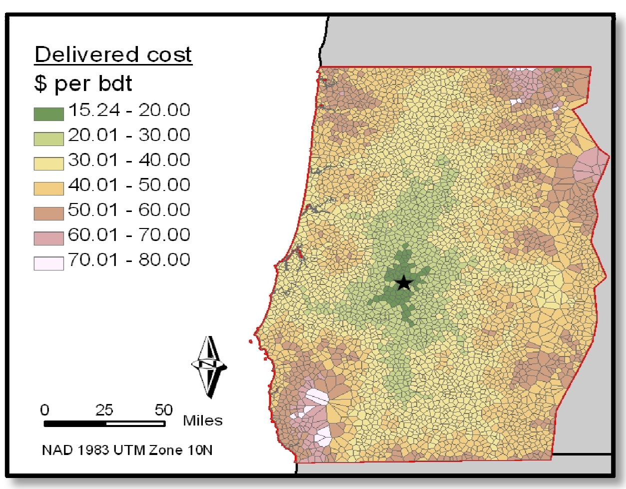


Figure 3. Estimated transportation costs of residues originated from each Thiessen polygon.

Summary

A methodology has been developed to spatially model forest residue stocks, flow, and transportation costs across a large landscape. The application and verification of the methodology is ongoing and has not been completed yet. This study will be completed by year's end and readers are encouraged to contact the authors for detailed methods and additional results. Upon successful completion, this study is expected to provide a useful model to estimate woody biomass supply and costs at different demand scales and facility locations, which will be critical information in determining the economically efficient scale and optimal location of biomass facility.

Acknowledgements

The authors would like to thank Deborah Page-Dumroese, Jim Archuleta, Greg Jones, Tyron Venn, Dan Loeffler and Edward Butler for their useful inputs and discussions, and assisting with spatial data preparation. This study was funded by a Woody Biomass, Bioenergy, and Bioproducts grant from U.S. Forest Service Research and Development, with significant cost match and in-kind support from the University of Montana.

Literature Cited

Chung, W. and Sessions, J. 2003. NETWORK 2000: A Program for Optimizing Large Fixed and Variable Cost Transportation Problems. In: G.J. Arthaud and T.M. Barrett (eds.) Systems Analysis in Forest Resources, Kluwer Academic Publishers. pp. 109-120.

Gan and Smith 2006 Gan, J. and C. Smith. 2006. Availability of logging residues and potential for electricity production and carbon displacement in the USA. Biomass and Bioenergy 30(12):1011-1020.

Jones, G., D. Loeffler, D. Calkin, and W. Chung. 2010. Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return. Biomass and Bioenergy 34(5): 737-746. doi:10.1016/j.biombioe.2010.01.016

U.S. Department of Energy. 2011. U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry. R.D. Perlack and B.J. Stokes (Leads), ORNL/TM-2011/224. Oak Ridge National Laboratory, Oak Ridge, TN. 227p.

Productivity and cost analysis of a mobile pyrolysis system deployed to convert mill residues into biochar

Woodam Chung[1], Dongyeob Kim[2], and Nathaniel Anderson[3]

Abstract

Forest and mill residues are a promising source of biomass feedstock for the production of bioenergy, biofuels and bioproducts. However, high costs of transportation and handling of feedstock often make utilization of forest residues, such as logging slash, financially unviable. As a result, these materials are often considered waste and left on site to decompose or pile-burned to reduce wildfire risk and open space for regeneration. As an alternative, in-wood processing of forest biomass with a small scale, mobile biomass conversion unit that can be deployed near the source of feedstock would generate a marketable, higher density product that could be shipped off site. However, private investment in these technologies is driven primarily by financial performance, which is often unknown for new technologies with limited deployment in the forest sector. In this study, we used a commercially available mobile pyrolysis system to characterize the conversion rate and system productivity and costs of the system. As a first step prior to deploying the system for in-wood applications, we deployed the system at a sawmill to convert mill residues into biochar. Our financial analysis reveals that the mobile pyrolysis system has the potential to enhance the economic value of forest residues, but financial performance is sensitive to a range of different operational variables, including system productivity and biochar conversion rate.

Keywords: biochar, pyrolysis, woody biomass, mill residues

Introduction

Forest and mill residues are a promising source of biomass feedstock for the production of bioenergy, biofuels and bioproducts. However, high costs of transportation and handling of feedstock often make utilization of forest residues, such as logging slash, financially unviable. In general, higher transportation costs resulting from low local and regional demand for residues negatively impact the financial viability of forest operations by potentially turning previously marketable byproducts into waste materials with disposal costs. Despite its challenges, some mills in the Rocky Mountain region have responded to shrinking residue markets by integrating the production and marketing of

[1] Department of Forest Management,College of Forestry & Conservation,University of Montana, Missoula, MT 59812, woodam.chung@umontana.edu

[2] Department of Forest Management,College of Forestry & Conservation,University of Montana, Missoula, MT 59812, dongyeob.kim@cfc.umt.edu

[3] Rocky Mountain Research Station, USDA Forest Service, Missoula, MT 59807. nathanielmanderson@fs.fed.us

value-added products traditionally made from forest and mill residues, including landscaping materials, animal bedding, compost, and wood pellets. Others have explored options for using biochemical or thermochemical conversion technologies to produce liquid biofuels, chemicals, and other high-value bioproducts (Briens 2008). Depending on the feedstock used and the substitutability of end products, these outputs have potential to offset fossil fuel use and associated emissions with renewable forest resources. Furthermore, they can improve energy security by displacing imported fuels and petrochemicals with domestic biomass energy products.

A large body of research is devoted to laboratory and pilot scale study of thermochemical conversion of woody biomass (Mohan et al. 2006, Kumar et al. 2009, van der Stelt et al. 2011), and an increasing number of companies are developing and marketing commercial technologies for biomass conversion. Especially, several companies manufacture distributed-scale conversion systems that can be deployed near the source of feedstock to avoid long haul transportation of bulky woody biomass (e.g., Biochar Solutions 2011). For forest industry firms, the decision to invest in a thermochemical conversion system for processing residues, however, hinges on the cost structure and financial performance of such an operation. Unfortunately, there is a high degree of uncertainty related to the performance of these systems and little market data to inform the marketing of their outputs, especially for biochar and bio-oil. This is primarily due to the fact that distributed pyrolysis systems are not yet widely deployed in industrial settings, resulting in a lack of economic data and market transactions for products. Existing studies tend to rely on theoretical production estimates rather than empirical data collected during manufacturing operations (e.g., Sorenson 2010, Badger et al. 2011, Brown et al. 2011). To date, no study has examined the use of distributed-scale thermochemical conversion using work study methods to quantify costs, productivity, and financial performance.

The objective of this study is to evaluate a commercially available system in the context of co-locating with forest industry operations. Specifically, we: (1) observed a mobile pyrolysis reactor operating at a sawmill in Colorado, (2) collected shift-level production data to characterize conversion rate and system productivity and costs, and (3) evaluated the net present value (NPV) of the operation in light of a cost structure that is realistic for the industry . This critical new knowledge is needed by technology firms, investors, and managers to evaluate the potential costs and benefits of integrating distributed-scale thermochemical processing systems into existing operations.

Methods

In this study, we used a small scale mobile pyrolysis system manufactured by Biochar Solutions Incorporated (BSI, Carbondale, CO). The system was engineered to produce biochar from biomass including agricultural residues and wood waste. This small-scale mobile pyrolysis system produces biochars with high fixed carbon content and high sorption using an exothermic reaction at temperatures between 350 and 750 ℃. Energy gas and heat are generally considered co-products of biochar production. Though a fraction of the gas stream could technically be condensed into bio-oil, the system does not produce a liquid output.

Data collection and productivity study

A system productivity study was designed to evaluate the production and financial performance of a BSI mobile pyrolysis system deployed at a sawmill in Pueblo, CO. Data collection was carried out at the site for 25 working days in October and November, 2011. Two different types of mill residues were used as feedstock in thermochemical biomass conversion: green mixed conifer mill residues and beetle-killed mill residues. Mixed conifer mill residues were composed of ponderosa pine (Pinus ponderosa, 90%) and other conifer tree species (10%), such as Douglas fir (Pseudotsuga menziesii). Beetle-killed mill residues were produced from beetle-killed lodgepole pine (Pinus contorta) harvested from White River National Forest in northwest Colorado. Both mill residues were preprocessed prior to the conversion through chipping, grinding, and screening to less than 3-inch particle size.

The BSI pyrolysis system was operated by either one or two operators in one 8-hour shift per day during the 25-day study period. The system was started in the morning by turning on the blower and initiating combustion in the first stage reactor with a propane torch. After startup, system operation typically included four steps: feedstock loading, feedstock conveying and drying, thermochemical conversion, and biochar collection. First, a front end wheeled loader is used to load preprocessed feedstock into a hopper. Feedstock is then slowly moved into the reactor through a conveyor system, while being dried by heat generated from a thermal oxidizer exhaust stack. The reactor converts feedstock into biochar, which is collected into barrels in two different forms: coarse biochar from a liquid cooled auger and dust removed from the gas stream by a cyclone.

To estimate the system productivity, we collected shift-level time study data during operation including start time, end time, weather conditions, and delays. Start time was measured when the system blower was turned on at the beginning of each shift, and end time was measured when the entire system was shut down and the operators left the site. In our study, delays were defined as any break times longer than 10 minutes in blower operation, with an assumption that the system does not produce biochar when the blower is off. To estimate system productivity and conversion rate on per unit weight basis, the total weight of feedstock was measured using an in-ground certified platform truck scale at the site at the beginning of each shift and the weight of biochar chips and dust output in barrels was measured using an electronic floor scale. In addition, the pressure and temperature of reactors and gas-paths of the BSI system were monitored and recorded with a computer system during the operation.

Productivity and biochar conversion rate are important measures of pyrolysis system performance. In this study, we define shift-level productivity as a ratio of the amount of feedstock consumed during the shift in green-tons (gt) to productive machine hours (PMH, abbreviated pmh in units). Gross level productivity of the system can be then estimated by compiling shift-level data for the entire field study period. We calculated productivity on a PMH basis instead of using scheduled machine hours (SMH), because the BSI pyrolysis system used in this study is an early design, and stable utilization rates have not been established for the system. In addition, our productivity measure is based on the amount of feedstock consumption rather than biochar production because several cost factors considered in the financial analysis depend on feedstock characteristics, such as feedstock loading and preprocessing costs, and because feedstock throughput is an important metric when considering pyrolysis systems for management of biomass byproducts, including mill residues. Conversion rate was defined as a mass ratio of the total produced biochar to the total consumed feedstock during the field production. The total amount of produced biochar includes biochar chips and dust, which are both marketable products of the operation.

Calculating machine rates and operation costs

We estimated pyrolysis system costs on a dollar per green-ton of feedstock basis using costs broken into three operational categories: feedstock preparation, pyrolysis conversion, and biochar bagging. Feedstock preparation includes feedstock grinding, screening and loading operations. Each operation requires the use of machinery, such as a tub grinder, rotary screener, loader, pyrolysis system, and biochar bagging equipment. The cost of each operation can be then estimated using a standardized machine hourly cost (i.e., machine rate) required for the operation, and machine productivity.

To calculate machine rates for individual machines used in the pyrolysis operations, we used widely accepted standard methods for machine rate calculations (Brinker et al. 2002). We obtained the machine rate parameters for a tub grinder and a wheel loader from the default values suggested in the Forest Residue Trucking Simulator v 5.0 (FoRTS v 5.0; USDA Forest Service 2012), while the price of the screener was obtained from the machine owner. For the BSI pyrolysis system, most machine rate parameters were obtained from the manufacturer's suggestions except for the PMH per year of the machine. We assumed the machine would productively operate for 8 hours a day and 260 days per year.

For machine productivity, the default values from FoRTS v.5 were used for a tub grinder and a wheel loader, which are 15 gt pmh^{-1}, 60 gt pmh^{-1}, respectively. For the screening equipment, a productivity of 15 gt pmh^{-1} was used as the operator's estimate. The productivity of the BSI pyrolysis system observed during the field study was used in the cost calculation. Biochar bagging costs were estimated based on the pyrolysis system owner's suggestion, which was \$40 $yard^{-3}$ for bagging operation costs and \$10 for each cubic yard bulk bag. To be consistent with other cost measures, these bagging operations costs were converted into dollar per green-ton of feedstock using conversion rate and biochar density observed during the field study.

Results and Discussion

BSI pyrolysis system productivity

During a total of 25 days of our field study, the pyrolysis system was productive for 22 days and undergoing maintenance for 3 days due to unexpected mechanical problems. We did not include this unexpected maintenance period in our productivity analysis. Total hours worked during 22 working days were 167.0 hours ranging from 3.8 to 10.2 hours per working day or an average of 7.6 hours per shift. Hours worked in each shift varied depending on operators' working schedules, pyrolysis system performance, and weather conditions. The system operated in the open, and was not operated during heavy rain or snow. There were a total of 31.4 hours of delays recorded during 22 working days with an average of 1.4 hours of delay per shift. Most delays were mechanical problems such as reactor clogging and auger malfunction.

A total of 23.4 gt of feedstock were consumed during the field study, while a total of 3.3 tons of biochar was produced, for an observed conversion rate of 14.1% by mass. The biochar production amount includes both biochar chips and dust. During the field study, we were able to measure the weight of biochar chips produced at the end of each shift, but biochar dust was measured only when the dust-collecting barrel was removed from the system and replaced, normally once every 2 to 3 shifts. To estimate the shift-level biochar dust production, we calculated a ratio of dust to chips using the gross amount of production of each product, and then multiplied the ratio (0.315) by shift-level biochar chip production. Based on the observed gross feedstock consumption and productive work hours over the 22 working days, the productivity of the BSI pyrolysis system is estimated as 0.172 gt pmh^{-1}. The shift-level productivity ranged from 0.126 to 0.241 gt pmh^{-1}. This wide variation in shift-level productivity indicates that the system did not run consistently during the observation period, probably due to mechanical reactor clogging that was not recorded as delay.

Costs of pyrolysis operation

Machine rates estimated for a tub grinder, a rotary screener, and a wheel loader used for feedstock preparation are \$163.81, \$39.78, and \$78.86 pmh^{-1}, respectively. The machine rate of the BSI pyrolysis system is \$48.07 pmh^{-1}. Total feedstock preparation costs are estimated as \$14.88 gt^{-1} of feedstock. Among the three individual operations of feedstock preparation, grinding is the most expensive component, accounting for 73% of the total feedstock preparation costs. The cost of pyrolysis conversion using the BSI system is estimated as \$279.48 gt^{-1} based on the system machine rate and observed system productivity. Biochar bagging cost is estimated as \$59.87 gt^{-1}. In the bagging cost calculation, a biochar density of 0.141 g cc^{-1} (Anderson et al. 2012) and a conversion rate of 14.1% are used. In summary, the total cost of the entire pyrolysis operation for biomass-to-biochar conversion is estimated as \$354.23 gt^{-1}, and the conversion process is the most expensive component of the operation, accounting for 79% of the total cost.

Conclusions

A mobile pyrolysis system was successfully deployed to a sawmill and used to process mill residues into biochar. Results show that at the productivity and conversion rates observed, this system might not be financially viable as a stand-alone enterprise. However, empirical data and observation of the system show clear opportunities for technical and operational improvements that could increase the productivity of this system, many of which have already been undertaken by the companies cooperating in this research. The pyrolysis system used in this study is a small-scale conversion system designed for mobility, and can be easily trailer mounted. We believe future studies should also investigate in-woods applications of the system. With enhanced consistency in operation and higher productivity, the system has the potential to improve the utilization of forest residues that would otherwise be burned in place.

Acknowledgements

The authors would like to thank Biochar Solutions Incorporated and Pueblo Wood Products, especially Jonah Levine and Brad Dunmire, for participating in this study and generously providing time, resources, and information. Dan McCollum, Dan Loeffler, and Edward Butler assisted with field operations and data collection. This research was funded by a Woody Biomass, Bioenergy, and Bioproducts grant from U.S. Forest Service Research and Development, with significant cost match and in-kind support from the University of Montana, Biochar Solutions Incorporated, and Pueblo Wood Products.

Literature Cited

Briens C, Piskorz J, Berruti F. Biomass valorization for fuel and chemicals production - a review. Int J Chem Reactor Eng 2008;6(1):-.

Anderson N, Page-Dumroese D, Jones JG, McCollum D, Baker S, Loeffler, D. A comparison of producer gas, biochar, and activated carbon from two thermochemical conversion systems used to process forest biomass. Biomass and Bioenergy in review; -.

Mohan D, Pittman Jr C, Steele P. Pyrolysis of wood/biomass for bio-oil: a critical review. Energy Fuels 2006;20:848-89.

Kumar A, Jones D, Hanna M. Thermochemical biomass gasification: a review of the current status of the technology. Energies 2009;2(3):556-81.

van der Stelt M, Gerhauser H, Kiel J, Ptasinski K. Biomass upgrading by torrefaction for the production of biofuels: a review. Biomass Bioenerg 2011;35:3748-62.

Biochar Solutions, Incorporated (BSI). BSI biochar base unit: technical specifications v 3.0; 2011.

Sorenson CB. A comparative financial analysis of fast pyrolysis plants in Southwest Oregon [dissertation]. Missoula (MT): University of Montana; 2010.

Badger P, Badger S, Puettmann M, Steele P, Cooper J. Techno-economic analysis: preliminary assessment of pyrolysis oil production costs and material energy

balance associated with a transportable fast pyrolysis system. Bioresour 2011;6(1):34-47.
Brown AL, Brady PD, Mowry CD, Borek TT. An economic analysis of mobile pyrolysis for Northern New Mexico forests. Albuquerque (NM): Sandia National Laboratories, US DOE; 2011 Dec. Report No.: SAND2011-9317.
Forest Operations Research Unit, USDA Forest Service [Internet]. Auburn, AL; 2005. Forest Residue Trucking Simulator (FoRTS) v. 5. Available from: http://www.srs.fs.usda.gov/forestops/tools.html [last accessed on 6/7/2012]

Costs and Productivities of Forest Biomass Harvesting Operations: A Literature Synthesis

William R. Coltrin[1], Sang-Kyun Han[2] and Han-Sup Han[3]

Abstract

Forest biomass has the potential to generate a significant amount of renewable energy in the US. However, costs and productivities of biomass harvesting are highly variable and remain relatively unknown, leaving it difficult for land managers to plan biomass operations. In this study, we have reviewed published and unpublished to broaden our knowledge on biomass harvesting cost and productivity. A database was developed for equipment options that are commonly used in biomass harvesting for their 2012 hourly machine costs. The database included typical harvesting productivities and costs for various harvesting system designs, and each equipment option used to collect, process, and transport biomass for energy. The costs and productivities of harvesting activities were affected by specific site and stand conditions such as machine selection and configuration, pre-haul cycle times, tree size, skidding distance, amount of volume removed, ground slope, moisture contents of material, and road classification type. Costs and productivities were then summarized from the literature and expert opinions. Three different biomass harvesting operations logistics were identified: 1) biomass recovery, where slash is collected after sawlog harvesting is completed, 2) whole tree biomass, where whole trees are removed in forest restoration and fire hazard reduction treatments, and 3) integrated harvesting, where sawlog trees and biomass trees are removed simultaneously in mechanical fuel reduction treatments. Integrated harvesting costs ranged from $42.98 and $50.49 per bone dry ton. Whole tree harvesting costs ranged from $30.21 to $42.98 per bone dry ton. Biomass recovery costs ranged from $17.33 to $28.10 per bone dry ton. This database of biomass harvesting costs and productivities can be used as an effective tool for forest managers to plan for biomass operations across a wide range of harvesting systems and machine configurations, stand conditions, and site conditions.

Introduction

Commercial logging and fuel reduction thinning treatments often generate large amounts of forest residues consisting of un-merchantable and small diameter trees, tree tops, limbs, and chunks, and are produced after various forest management activities Forest residues can be used to generate electricity and heat in direct-combustion systems, providing the nation with a significant amount of renewable energy (Perlack et al. 2005). Forest residues in the United States are rarely harvested specifically for energy generation purposes (Miller et al. 1987), due to the low market value of wood

[1] Research Associate, Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA.
[2] Research Associate, Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA.
[3] Professor, Department of Forestry and Wildland Resources, Humboldt State University, Arcata, CA.

chips or hog fuel and high costs of extraction (Han et al. 2004; Spinelli and Visser 2009).

Because of high costs associated with harvesting and low market values, forest residues are treated as wasted resources and are often left on-site and burned after harvesting. However, open burning of forest residues creates negative environmental impacts. Carbon dioxide emissions from open air burning exacerbate the threat of climate change (Jones et al. 2010). Further, forest residues burned in the woods have the potential to escape to other areas causing further wildfire hazards. Because of this, forest residue extraction is an attractive alternative to open burning (Hollenstein et al. 2001). In addition, biomass extraction can assist with site preparation measures for re-planting and potentially generate revenue from the sale of hog fuel/wood chips for energy. As biomass removal from various forest management activities increases in demand, it is important to understand the costs and productivities associated with extraction.

There have been many field-based studies evaluating biomass harvesting operations in the US which can be used to understand costs and productivities of site-specific stand conditions, management scenarios, and equipment selection. These studies provide valuable information of biomass harvesting factors that are attributed to cost and productivity, but their harvesting productivity and cost information is highly variable. Furthermore, it is often difficult to compare or understand the harvesting productivity and cost figures because of operations work environment and assumptions used in cost analyses are not clearly presented (Rummer 2008). Cost models such as Fuel Reduction Cost Simulator (FRCS) (Fight et al. 2006) and STHarvest (Hartsough et al. 2001) have been developed and used to estimate the removal of smaller size biomass trees from various biomass harvesting systems. However, some harvesting productivity estimation functions used in these models are based on the data collected from larger sawlog harvesting studies and have limitations in estimating costs of removing trees smaller than the range of tree sizes that were used in these models (Bolding et al. 2009). Expert opinion methods have been also used to assess costs for biomass harvesting systems (Coltrin et al. 2012). This method works well for the scenarios within the study site; however the expert opinion method may be limited to specific local areas because their opinions capture intangible costs or restrictions that are not present in other regions, allowing for inaccurate estimates outside the study area (Rummer 2008).

Assessments of biomass harvesting system costs and productivities are difficult to implement due to the many variables that can exist within a particular harvesting method and stand condition. Typical biomass harvesting methods often include the use of equipment designed for sawlog removal. Machines designed to handle large trees are used to recover forest residues with low market values. Because of this, total operating costs (stump-to- truck) for biomass removal tend to be generally expensive, compared to the revenue from wood chips or hog fuel. Equipment selection is also an important variable affecting cost and productivity. Machine sizes should be appropriately matched with the amount and size of material being handled or processed

(Han et al. 2004). Stand variables such as volume of removal, tree size, skidding distance, and slope can affect cost and productivity as well (Watson et al. 1986; Miller et al. 1987; and Pan et al. 2008). Cost and productivity assessments across a broad management scenario are difficult to implement due to these variables. Because of this, a general comprehensive planning model is needed to understand costs and productivities of biomass harvesting systems across a wide range of sites and stand conditions.

The purpose of this study is to improve our knowledge on cost and productivity of biomass harvesting systems that are commonly used in the US through development of a database of typical biomass operations logistics and system configurations. This includes stump-to-loaded-truck costs and productivities for felling, handling, and comminution of each type of biomass harvesting system. The specific objectives are to 1) identify the types of biomass harvesting systems and equipment that are commonly used in biomass collection, processing and transportation, and 2) develop general cost and productivity figures for each piece of equipment throughout various biomass harvesting systems. The outcomes of this study should be useful for forest managers to understand appropriate biomass system selection and associated costs and productivities.

In this study, a literature review identified 13 published and un-published papers that presented costs and productivities of biomass harvesting operations. Each paper examined in this study presented costs in $/ton and productivities in tons/productive machine hour (PMH). Other papers that presented 1) biomass harvesting costs in $/acre or 2) costs and productivities for biomass harvesting for purposes other than energy generation (e.g. pulpwood harvesting) were not included in this study. Experimental biomass operations using cut-to-length harvesting were not included in this study, due to the small sample size (Bolding and Lanford 2005) of that configuration. We also contacted the manufacturers and contractors who have experience with biomass harvesting equipment to obtain machine productivity specifications. The results of the literature review and expert opinions were combined to develop a database that can be used to estimate various biomass harvesting systems costs and productivities.

Biomass harvesting systems and methods

Three biomass harvesting system types were identified in the literature: 1) biomass recovery, 2) whole tree harvesting, and 3) integrated harvesting. Each system has different methods of operations, depending on site- and stand-specific conditions, and management purposes.

Biomass recovery operations

Biomass recovery operations commonly take place after sawlog harvesting has occurred. The objective of recovery is to collect logging slash and comminute material using a grinder. This can be done using two different methods (i.e. pile-to-pile vs.

centralized grinding). With the first method, a loader is used to collect material and feed it into a grinder at the landing. After all material has been comminuted, the loader and the grinder move to the next pile. The other method comminutes the material at a central processing area, where the grinder and the loader are stationary. Secondary transport vehicles, such as dump trucks, hook-lift trucks, or roll-off container trucks, are used to deliver material from multiple landings to the central processing area. An additional loader is used at the landings to load material into the secondary transport vehicle. The secondary transport vehicle delivers the material to the central processing area, unloads the material, and travels back to the landing for further loading. Centralized methods are often preferred because the grinder can be effectively utilized by minimizing delays associated with moving from landing to landing (Harrill and Han 2010). In addition, areas that are difficult to access with low-boys hauling a grinder can effectively be accessed with pre-hauling vehicles to collect logging slash (Han et al. 2010).

Whole tree harvesting

Whole tree harvesting involves mechanical thinning or forest restoration operations that remove whole trees from the treatment area. In whole tree harvesting, tops and limbs are processed at the landing, rather than the stump. Common machine configurations for whole tree harvesting are 1) feller-buncher, 2) skidder, 3) loader, and 4) chipper or grinder. The resulting product is in the form of energy wood chips or hog fuel. Since no sawlog component of this system is produced, the need for additional sawlog processing machines is not required. This system of biomass harvesting has been used as an effective method to reduce fire hazards by removing small suppressed trees that can act as ladder fuels for intermediate, co-dominant and dominant trees in the treatment area (Agee 1993). This system is typically designed to remove small-diameter trees (e.g. < 5" dbh) in high density stands prone to catastrophic wildfires. In addition, whole tree harvesting is an effective tool for forest restoration purposes, by removing undesirable tree species which are processed as an energy feedstock material.

Integrated harvesting

Integrated harvesting is defined as harvesting un-merchantable biomass trees for energy and merchantable sawlog trees for dimensional lumber simultaneously (Hudson et al. 1990). Machines designed to harvest sawlogs are also used to harvest biomass trees. Common machine configurations for integrated harvesting are 1) feller-buncher, 2) skidder, 3) dangle-head processor or stroke-boom delimber to remove limbs and tops, 4) loader, and 5) chipper or grinder. This harvesting method is common for fire hazard reduction treatments on National Forests, similar to whole tree harvesting purposes. However, the functions of integrated harvesting are slightly different from whole tree harvesting. In integrated harvesting, sawlog trees are harvested in conjunction with biomass trees that effectively reduce ladder fuels and crown bulk densities, thus slowing the potential spread of wildfire (Keyes and O'Hara 2002). The feller-buncher creates bunches consisting of sawlog trees and biomass trees within one or two separate piles. If the biomass piles are separated from sawlog tree piles, then skidding biomass trees generally takes place after completion of sawlog skidding and processing. By doing this, a chipper can be brought to the landing to process small-diameter whole biomass trees and tree tops generated from sawlog tree processing. A grinder may be brought in to the landing to process left over slash material. When bunches of biomass trees and sawlog trees are piled and skidded together, a grinder is utilized to process all material.

Costs and productivities of biomass harvesting and transportation

Biomass recovery operations

Biomass recovery operations are performed with either centralized or pile-to-pile method, depending on: 1) the amount of available logging slash, 2) steepness of terrain that dictates the available landing space for centralized grinding, and 3) round trip cycle time for pre-hauling from landing to centralized grinding location. Given a scenario with ample amounts of slash, short pre-haul cycle times, and large centralized landing sites, the centralized grinding method is known to reduce operating costs and increase productivity for biomass recovery operations. A study by Harrill and Han (2010) showed significant cost savings when hook-lift trucks pre-hauled biomass to be comminuted at a centrally located grinder and loader.

This system logistic increased the productivity of the grinder (the most expensive operation in the system at approximately $600 per PMH) by reducing grinder delay time from moving from landing to landing. However, pre-hauling costs increased when the truck spent more time hauling material, rather than distance to the centralized grinding area. Road classifications such as spur road, dirt road, one-lane gravel road, and two-lane gravel road are important factors that determine the travel time and subsequently overall pre-hauling costs (Harrill and Han 2010; Han et al. 2010). An additional factor affecting biomass recovery costs and productivities are found in the arrangement and type of slash piles. The study by Harrill and Han (2010) developed five slash pile categories and determined that loading pile class #2 into hook-lift trucks was the most cost effective pile class due to the large material size and parallel arrangement of material.

In addition, the biomass recovery method creates indirect cost savings because it eliminates the need to dispose slash through open burning. This method can reduce site preparation costs associated with burning and herbicide applications. After burning slash piles, or broadcast burning, fire-prone species often sprout back necessitating herbicide applications in order to reduce confer seedling competition with shrub species. The costs of burning and herbicide application can range from $350 - $800 per acre, depending on the density of fire-prone species (Alcorn 2012).

Whole tree harvesting

Cost and productivity of whole tree harvesting operations are affected by machine selection, tree size, skidding distances, moisture content of biomass trees and volume of removal. For example, a study by Pan et al. (2008) summarized mechanized harvesting of whole trees in a fuel reduction thinning treatment in northern Arizona. Small diameter ponderosa pine trees (< 5" diameter at breast height, dbh) were harvested to reduce the threat of catastrophic wildfire. In the whole tree category, no merchantable timber was extracted. This made it possible to select a smaller feller-buncher that was more cost effective at removing small diameter trees. A three-wheeled hot saw Valmet 603 was able to efficiently maneuver around intermediate, co-dominant and dominant trees while removing suppressed trees.

Tree size also affects cost and productivity. As tree size increases, productivity can increase for each machine in the system (Watson et al. 1986). Increases of skidding distance for whole tree removal tend to increase overall production costs by approximately $0.58/BDT per 100 feet skidding increase (Pan et al. 2008). In addition, the study by Pan et al. (2008) revealed that grinder production decreased as moisture content of biomass trees increased. Volume of biomass trees for removal also affects cost and productivity estimates. Miller et al. (1987) observed biomass harvesting of five tracts of pine and hardwood stands with varying volume of removal. For feller-buncher, the productivity increased the most as more volume of biomass trees were needed for removal, while skidding and chipping productivities were relatively unaffected.

Integrated harvesting

The cost and productivity analysis in integrated harvesting is different from biomass recovery and whole tree harvesting because costs are allocated to either the sawlog or biomass depending on the machine's activity involved with each product category (Puttock 1995). There are no felling and skidding costs for the biomass generated from sawlog production because by default, the sawlog production would generate biomass that does not require additional costs, such as limbs and tops from sawlog trees. However, felling and skidding small-diameter whole biomass trees cause additional costs to integrated harvesting.

Factors that affect cost and productivity for integrated biomass harvesting are tree size, skidding distances, and ground slope. For example, Han et al. (2004) found that biomass handling costs increased as tree size decreased. Vitorelo et al. (2012) revealed that skidding bunches of biomass trees were less productive than sawlog bunches. This was due to the low bulk density of bunches attributed to small tree sizes (3 to 9 inches dbh). A study by Coltrin et al. (2012) sent out surveys to contractors with experience conducting fuel reduction thinning treatments on National Forests. In that study, it was found that there were significant increases of costs for skidding biomass trees with increases in skidding distances. However, the amount of sawlog volume of removal did not affect overall biomass harvesting costs in integrated harvesting systems.

Changes in ground slope are also known to affect biomass operation costs. This is especially true with cable yarding systems (slope > 35%) because the costs of biomass harvesting outweigh the revenue from biomass for energy (Hochrien et al. 1998). Because of this, integrated cable yarding harvesting is rarely practiced. The study by Coltrin et al. (2012) found that only five cable yarding contractors participated in fuel reduction thinning treatments on National Forests in southern Oregon and northern California, likely due to the high costs of operations and low market value of hog fuel and wood chips. Because of this, data for cost and productivities of biomass cable yarding operations is lacking.

Development of a database of harvesting cost and productivity

In the biomass recovery method, four studies were reviewed (Anderson et al. 2010; Dodson 2010; Harrill and Han 2010; and Han et al. 2010). In the whole tree harvesting method, four studies were reviewed (Watson et al. 1986; Miller et al. 1987; Stokes 1992; and Pan et al. 2008). For integrated harvesting, seven studies were reviewed (Watson et al. 1986; Miller et al. 1987; Stokes 1992; Puttock 1995; Hartsough et al. 1997; Largo and Han 2004; and Bolding et al. 2009; and Vitorelo et al. 2012). From the literature review we analyzed average cost and productivity figures across a wide range of stand conditions and machine types and configurations for each biomass harvesting system. The expert opinions of Steve Morris Logging and Contracting (Morris 2012) and Peterson Pacific Corporation (Cumming 2012) were used to obtain machine productivities and costs for chippers, grinders, modified dump trucks, and loaders. These figures were used in conjunction with average cost and productivity figures from the literature review to develop a database of general cost and productivity figures for each biomass harvesting machine and system identified.

The following Tables 1, 2, and 3 can be used as a database for general cost and productivity figures for several different biomass harvesting methods, including biomass recovery (pile-to-pile and centralized grinding), whole tree harvesting (medium chipper with small trees, medium chipper with large trees, large chipper with small trees and large chipper with large trees), and integrated harvesting (chipping whole tree and grinding slash, and grinding whole tree and slash). Key assumptions in in calculating cost and productivities were: 1) feller-buncher and skidder utilization rate set at 65%, 2) pre-hauling vehicles utilization rate set at 80%, 2) grinder and loader utilization rate set at 60% for pile-to-pile operations and 80% for centralized operations, 2) 2011 initial machine prices, 3) wages and benefits set to $25 per hour, and 4) moisture content of biomass was assumed at 35%.

In addition to system costs, machine costs for each operation in each system were calculated. In general, biomass recovery systems were the least expensive systems, ranging in costs from $17.33 to $28.10 per BDT (Fig. 2). Whole tree biomass harvesting costs and integrated biomass harvesting costs were more expensive, ranging in cost for whole tree systems from $30.21 to $42.98 per BDT (Fig. 3), and integrated systems from $42.98 and $50.49 per BDT (Fig. 4).

Transportation to energy plant

In each system of biomass harvesting, the operation that incurs the most costs is transportation. Key factors that affect transportation costs are road types and moisture content of hog fuel/wood chips. Similar to pre-hauling costs, chip van transportation costs are dictated by time spent hauling material. A study by Rawlings et al. (2004) found that the travel speeds for chip vans varied depending on road type. For one-lane spur roads, gravel roads, two-lane highway, and interstate, the average travel speeds were 10.5 miles per hour (mph), 30 mph, 50 mph, and 60 mph, respectively. Because of this, transportation costs can significantly increase depending on the amount of time the chip van travels on each road type. Moisture content of biomass is an important variable affecting transportation costs from the landing to the end user. A study by Han et al. (2012) found that transportation costs for hauling biomass with 50% moisture content increased costs versus hauling biomass with 35% moisture content (Fig. 4). Careful attention should be given to lower biomass moisture content in order to reduce overall transportation costs.

Conclusion

This study examined biomass harvesting systems for energy production common in the U.S. It was found that biomass harvesting systems cost and productivity figures were widely variable, depending on numerous factors such as machine selection and configuration, and specific stand and site characteristics. Factors such as machine size, harvesting method, volume of removal, tree size, skidding distance, ground slope, and road types and conditions all affected cost and productivity of biomass harvesting. In general, the cost of biomass harvesting operations tended to be expensive due to the low market value of energy wood chips and hog fuel.

A literature review disclosed three general types of biomass harvesting: 1) biomass recovery, 2) whole tree harvesting, and 3) integrated harvesting. Biomass recovery operations were typically used for the collection of slash left over after conventional sawlog harvesting was completed. Whole tree and integrated harvesting were used for fire hazard reduction and forest restoration purposes, by removing small-diameter trees to reduce ladder fuels and crown bulk densities.

A database of costs and productivities of various biomass harvesting systems was developed from the literature review and from expert opinions of machine manufacturers and biomass harvesting contractors. Biomass recovery operations had the least expensive production costs ranging from $17.33 to $28.10 per BDT. Whole tree and integrated operations ranged from $30.21 to $42.98 per BDT, and $42.98 and $50.49 per BDT, respectively. The availability of slash already processed and piled at the landing from sawlog operations resulted in lower costs for collection and comminution of biomass recovery operations. Whole tree harvesting costs were less than integrated harvesting due to equipment selection options. In whole tree harvesting, smaller sized machines were selected to specifically handle small-diameter trees. Integrated harvesting costs were the highest because machines designed to handle and process sawlog trees were also handling and processing low value biomass trees.

The efforts of this study produced a database can be used as a general planning tool to assess biomass operation costs and understand productivity figures for various biomass harvesting configurations. Cost and productivity figures from this database can be applied to any stand situation in the United States to estimate general expected costs associated with operations. This database should not necessarily be used for site-specific planning purposes due to specific variables such as machine types, ground slope, skidding distance, pre-haul round trip cycle times, tree size, and volume of removal. However, this database does capture general expected costs of biomass harvesting that encompass many different stand situations and machine types.

Future research into biomass harvesting systems should include equipment innovation to handle and process small-diameter trees, and improvements in collection and comminution logistics. Improvements into these areas need to reduce overall harvesting costs, while increasing productivity. Until these improvements are made, or the market value of energy wood chips and hog fuel increases, slash disposal and fire hazard reduction treatments in the U.S. will remain difficult to implement due to high production costs.

References

Alcorn, A. 2012. Personal communication. Forester, Green Diamond Resource Company, Korbel, CA 95550

Agee, J. K 1993. Fire ecology of Pacific Northwest forests. Island Press, Washington, D.C., USA.

Anderson, N., W. Chung, G. Jones, and D. Loeffler. 2010. A productivity and cost comparison of hog fuel production using slash forwarding and in-woods grinding of cured harvest residues. In Proceedings of the 33rd Annual Meeting of the Council on Forest Engineering: Fueling the Future. Compiled by D. Mitchell and T. Gallagher. June 6 – 9. Auburn, AL.

Bolding, C.M. and B.L. Lanford. 2005. Wildfire fuel harvesting and resultant biomass utilization using a cut-to-length/small chipper system. Forest Prod. J. 55(12): 181-189.

Bolding, C.M., L.D. Kellogg, and C.T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in Southwest Oregon. *For. Prod. J*. 59(3): 35–46.

Coltrin, W.R., H-.S. Han, and S-.K. Han. 2012. A Survey on Costs to Contractors Conducting Mechanical Fuel Reduction Thinning Treatments on National Forests. Manuscript in preparation.

Cumming, L. 2012. Personal communication. Owner, Peterson Pacific Corporation, Eugene, OR 97401

Dodson, Elizabeth M. 2010. Some like it hot; some like it cold: Experience with biomass collection in western Oregon. Proc. June, 2010, Council On Forest Engineering (COFE) annual meeting, Auburn, AL. 6p.

Fight, R.D., B.R. Hartsough, and P. Noordijk. 2006. Users guide for FRCS: Fuel reduction cost simulator software. Gen. Tech. Rept. PNW-GTR-668. USDA Forest Serv., Pacific Northwest Res. Sta., Portland, OR. 23 p.

Han, H.-S., H. Lee, L. Johnson. 2004. Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. Forest Products Journal, 54 (2) (2004), pp. 21–27

Han, H.-S., J. Halbrook, and F. Pan. 2010. Economic evaluation of a roll-off trucking system removing forest biomass resulting from shaded fuelbreak treatments. Biomass and Bioenergy 34: 1006-16.

Han, H-.S., and L.R. Johnson. 2012. Biomass feedstock supply: Cost and life-cycle analysis. Proc. June, 2012. Forest Products Society annual meeting. Washington D.C.

Harrill, H., and H-S. Han. 2010. Application of hook-lift trucks in centralized logging slash grinding operations. Biofuels 1(3): 399-408.

Hartsough, B.R., E.S. Drews, J.F. McNeel, T.A. Durston, and B.J. Stokes. 1997. Comparison of mechanized systems for thinning ponderosa pine and mixed conifer stands. For. Prod. J. 47(11/12):59–68.

Hochrien, P.H. and L.D. Kellogg. 1988. Production and cost comparison for three skyline thinning systems. Western Journal of Applied Forestry 3(4):120-123

Hollenstein, K.; Graham, R. L.; Shepperd,W.D. 2001. Biomass flow in the western forests: simulating the effects of fuel reduction and pre-settlement restoration treatments. J. Forestry. 99, 12–19.

Hudson J., C. Mitchell and P. Storry. 1990. Costing integrated harvesting systems for wood supply. Dep. For, Univ. Aberdeen. Aberdeen, Scotland. 14p.

Jones, G., D. Loeffler, D. Calkin, and W. Chung. 2010. Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return. *Biomass Bioenergy*. 34(5):737–746.

Keyes, C., and K. L. O’Hara. 2002. Quantifying stand targets for silvicultural prevention of crown fires. Western Journal of Applied Forestry **17**:101–109.

Largo, S., and H-S. Han. 2006. Economics of an integrated harvesting system in a fuel reduction thinning in western Montana. Proc. July, 2009 Council On Forest Engineering (COFE) annual meeting, Hot Springs, AR. 6p.

Miller, D.E., T.J. Straka, B.J. Stokes, and W.F.Watson. 1987. Productivity and cost of conventional understory biomass harvesting systems. For. Prod. J. 37(5): 39-43.

Morris, S. 2012. Personal communication. Owner, Steve Morris Logging & Contracting, Blue Lake, CA 95525

Pan F, Han H, Johnson LR, Elliot WJ. 2008. Production and cost of harvesting, processing, and transporting small-diameter (≤5 inches) trees for energy. For. Prod. J. 58(5): 47-52

Perlack RD, Wright LL, Turhollow AF, Graham RL, Stokes BJ, Erbach DC (2005) *Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion Ton Annual Supply* (Oak Ridge National Laboratory, Oak Ridge, TN), ORNL/TM-2005/66.

Puttock GD. 1995. Estimating cost for integrated harvesting and related forest management activities. Biomass and Bioenergy; 8(2):73-79.

Rawlings C; Rummer B; Seeley, C; Thomas, C; Morrison, D; Han, H; Cheff, L; Atkins, D; Graham, D; Windell, K. 2004. A study of how to decrease the costs of collecting, processing and transporting slash. Montana Community Development Corporation, Missoula, MT

Rummer, B. 2008. Assessing the cost of fuel reduction treatments: a critical review. *Forest Policy and Economics* 10: 355–362.

Spinelli, R. and R. Visser. 2008. Analyzing and estimating delays in wood chipping operations. Biomass and Bioenergy 33(3): 429-33.

Stokes, B.J. 1992. Harvesting small trees and forest residues. Biomass and Bioenergy. 2: 131-147.

Vitorelo, B. and H-.S. Han. 2011. Cost and productivity of two mechanical fire hazard reduction methods: mastication and thinning. MS Thesis, Humboldt State University, Arcata, CA 85 pp.

Watson, W.F., B.J. Stokes, and I.W. Savelle. 1986. Comparisons of two methods of harvesting biomass for energy. *Forest Products Journal* 36(4):63-68.

Table 1. Stump-to-truck costs and productivities for five biomass recovery systems.

Biomass Recovery Systems		Machine Rate $/PMH	Productivity BDT/PMH	Production Cost $/BDT
Pile-to-Pile Operations				
Biomass recovery system 1				
Loading	Large Loader with Grinder, On-site	188.93	30.00	6.30
Processing	On Site Horizontal Grinder	441.33	40.00	11.03
Total	Stump to Truck			17.33
Biomass Recovery System 2				
Loading:	Large Loader with Grinder, On-site	188.93	30.00	6.30
Processing:	On Site Horizontal Grinder	441.33	40.00	11.03
Hauling:	Dump Truck w/ Tail Closed - Ground Biomass	104.29	14.41	7.24
Loading:	Front End Loader	185.85	80.00	2.32
Total	Stump to Truck			26.89
Centralized Operations				
Biomass Recovery System 3				
Loading:	Large Loader with Dump Truck	149.38	32.00	4.67
Hauling:	Dump Truck- Modified - Loose Residue	87.46	12.65	6.91
Loading:	Large Loader with Grinder, Centralized	141.70	40.00	3.54
Processing:	Centralized Horizontal Grinder	369.48	40.00	9.24
Total	Stump to Truck			24.36
Biomass Recovery System 4				
Loading:	Large Loader with Roll-off	149.38	22.00	6.79
Hauling:	Roll Off Container - Loose Residue	78.31	9.81	7.98
Loading:	Large Loader with Grinder, Centralized	141.70	40.00	3.54
Processing:	Centralized Horizontal Grinder	369.48	40.00	9.24
Total	Stump to Truck			27.55
Biomass Recovery System 5				
Loading:	Large Loader with Hook-lift	149.38	22.00	6.79
Hauling:	Hook-Lift Container - Loose Residue	83.75	9.81	8.54
Loading:	Large Loader with Grinder, Centralized	141.70	40.00	3.54
Processing:	Centralized Horizontal Grinder	369.48	40.00	9.24
Total	Stump to Truck			28.10

Table 2. Stump-to-truck costs and productivities for six whole tree biomass harvesting systems identified in this study.

Whole Tree Harvesting Systems		Machine Rate $/PMH	Productivity BDT/PMH	Production Cost $/BDT
Whole Tree System 1				
Felling:	Medium Biomass Feller Buncher	139.09	10.00	13.91
Skidding:	Medium Biomass Skidder	130.71	12.00	10.89
Processing:	Medium Chipper - Small Trees (<5")	189.38	20.00	9.47
Total	Stump to Truck			34.27
Whole Tree System 2				
Felling:	Medium Biomass Feller Buncher	139.09	10.00	13.91
Skidding:	Medium Biomass Skidder	130.71	12.00	10.89
Processing:	Medium Chipper - Large Trees (>5")	189.38	35.00	5.41
Total	Stump to Truck			30.21
Whole Tree System 3				
Felling:	Large Biomass Feller Buncher	175.38	12.00	14.62
Skidding:	Large Biomass Skidder	154.43	14.00	11.03
Processing:	Large Chipper - Small Trees (<5")	300.45	30.00	10.02
Total	Stump to Truck			35.66
Whole Tree System 4				
Felling:	Large Biomass Feller Buncher	175.38	12.00	14.62
Skidding:	Large Biomass Skidder	154.43	14.00	11.03
Processing:	Large Chipper- Large Trees (>5")	300.45	40.00	7.51
Total	Stump to Truck			33.16
Whole Tree System 5				
Felling:	Medium Biomass Feller Buncher	139.09	10.00	13.91
Skidding:	Medium Biomass Skidder	130.71	12.00	10.89
Loading:	Large Loader with Grinder, On-site	251.91	40.00	6.30
Processing:	On Site Horizontal Grinder	441.33	40.00	11.03
Total				42.13

Whole Tree System 6				
Felling:	Large Biomass Feller Buncher	175.38	12.00	14.62
Skidding:	Large Biomass Skidder	154.43	14.00	11.03
Loading:	Large Loader with Grinder, On-site	251.91	40.00	6.30
Processing:	On Site Horizontal Grinder	441.33	40.00	11.03
Total				42.98

Table 3. Stump-to-truck costs and productivities for two integrated harvesting systems identified in this study.

Integrating Harvesting Systems		Machine Rate $/PMH	Productivity BDT/PMH	Production Cost $/BDT
Integrated System 1				
Felling:	Large Biomass Feller Buncher	175.38	12.00	14.62
Skidding:	Large Biomass Skidder	154.43	14.00	11.03
Loading	Large Loader with Grinder	251.91	40.00	6.30
Processing:	On Site Horizontal Grinder	441.33	40.00	11.03
Processing:	Large Chipper- Large Trees (>5")	300.45	40.00	7.51
Total	Stump to Truck			50.49
Integrated System 2				
Felling:	Large Biomass Feller Buncher	175.38	12.00	14.62
Skidding:	Large Biomass Skidder	154.43	14.00	11.03
Loading:	Large Loader with Grinder, On-site	251.91	40.00	6.30
Processing:	On Site Horizontal Grinder	441.33	40.00	11.03
Total	Stump to Truck			42.98

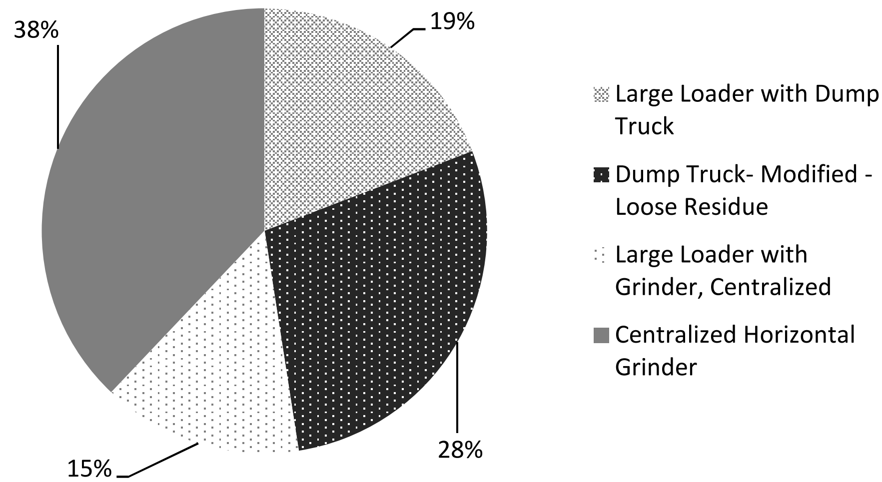


Figure 1. Percent of total production cost for a biomass recovery operation using a modified dump truck for pre-hauling loose forest residues to a centralized grinder. Hourly and total production costs for this system are $748.01/PMH and $24.36/BDT.

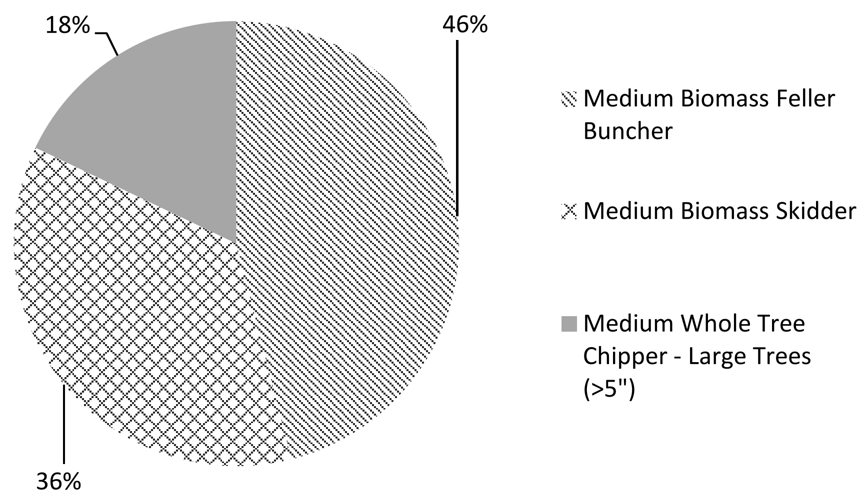


Figure 2. Percent of total production costs for a whole tree harvesting method using a medium sized feller-buncher, skidder, and chipper processing trees > 5”. Hourly and total production costs for this system are $459.18/PMH and $30.21/BDT.

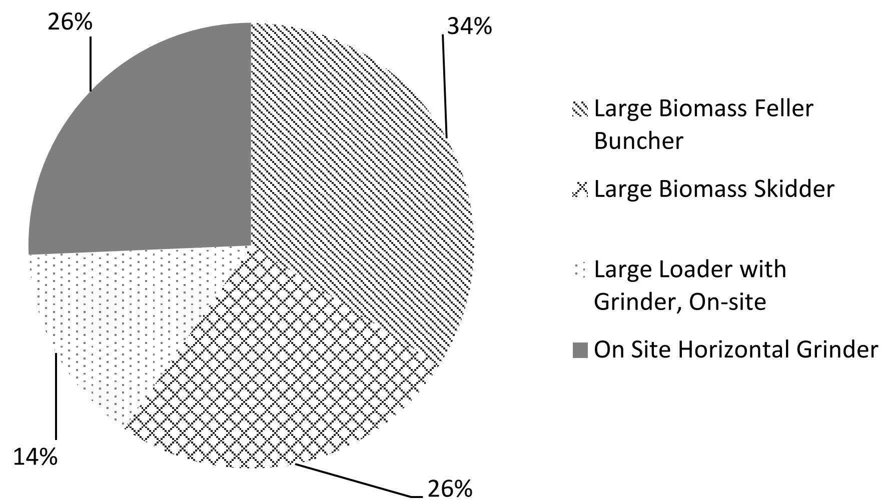


Figure 3. Percent of total production costs for an integrated biomass harvesting method using a large feller-buncher, skidder, loader, and on-site horizontal grinder. Hourly and total production costs for this system are $1,003.06/PMH and $42.98/BDT.

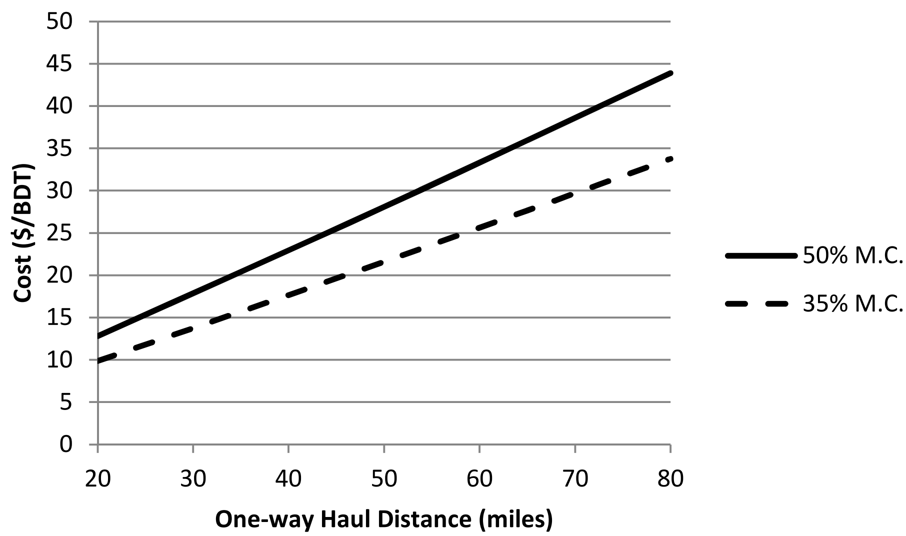


Figure 4. Hauling costs at two different moisture contents (MC) of biomass.

Harvesting Productivity and Costs When Utilizing Energywood From Pine Plantations of the Southern Coastal Plain, USA

(POSTER)

Joseph L. Conrad IV[1] and M. Chad Bolding[2]

Abstract

In order for woody biomass to make a significant contribution to the United States' energy portfolio, harvesting contractors must be able to economically harvest and transport energywood to conversion/processing facilities. We conducted a designed operational study on a southern pine clearcut in the Coastal Plain of North Carolina, USA, with three replications of three harvest prescriptions to measure harvesting productivity and costs when utilizing woody biomass for energy. The three treatments were (1) conventional roundwood only harvest (control); (2) an integrated harvest in which roundwood was delivered to traditional mills and residuals were chipped for energy use; and (3) a chip harvest in which all stems were chipped for energy use. The harvesting contractor in this study typically delivers 100-120 loads of roundwood per week and is capable of wet-site harvesting. Onboard truck roundwood costs increased from \$9.35 per green tonne in the conventional treatment to \$10.98 gt^{-1} in the integrated treatment as a result of reduced felling and skidding productivity. Energy chips were produced for \$19.19 gt^{-1} onboard truck in the integrated treatment and \$17.93 gt^{-1} in the chip treatment. Low skidding productivity contributed to the high chip costs in the integrated and chip treatments. Residual woody biomass was reduced from 18 gt ha^{-1} in the conventional treatment to 4 and 3 gt ha^{-1} in the integrated and chip treatments, respectively. This study suggests that until energywood prices appreciate substantially, loggers, especially wet-site loggers like the one in this study, are unlikely to reduce roundwood production to increase energywood production. This research provides unique information from a designed experiment documenting how producing energywood affects each function of the harvesting system.

[1] Assistant Professor of Forestry, University of Wisconsin-Stevens Point, jconrad@uwsp.edu
[2] Associate Professor of Forest Operations/Engineering, Virginia Tech, bolding@vt.edu
228 Cheatham Hall, Virginia Tech Department of Forest Resources and Environmental Conservation
Blacksburg, VA 24061

IMPROVING WOODY BIOMASS FEEDSTOCK LOGISITICS BY REDUCING ASH AND MOISTURE CONTENT

Jason B. Cutshall, Shawn A. Baker, W. Dale Greene[1]

Abstract

In this paper we compare a range of likely forest biomass harvesting systems including whole-tree chipping, clean chipping, conventional roundwood, and residue grinding to determine how each system affects woody biomass energy facilities, biomass harvesting firms, and forest landowners. Delivered costs for these systems were evaluated for a range of values for moisture content, ash content, tract size, tons of biomass removed per acre and at grinding decks, truck payload, haul distance, and diesel fuel price. Delivered cost per mmBTU decreased by over 50% for all systems as moisture content decreased from 55% to 30%. Whole tree chipping provided the lowest cost option ($4.39 per mmBTU) at ash content levels less than 1%, and unscreened grinding of clean chip residue produced the least expensive option at 5% ash ($2.87 per mmBTU). Tract size had minimal effects on any operation until the acreage declined below 40 acres. Clean chipping and roundwood systems were considerably more expensive than whole-tree chipping operations on all tract sizes. Costs declined significantly as truck payload increased and/or haul distance decreased. Fuel price increases directly increase cut and haul costs and limit economical haul distances accordingly.

Index Words: forest biomass harvesting, chipping, grinding, moisture content, ash content

Introduction

Higher market prices for fossil fuels as well as proposed policy changes to support renewable energy use and to reduce carbon emissions have recently led to a large number of bioenergy projects being announced which will consume woody biomass. Projects recently announced for North America could substantially increase wood energy capacity and potentially consume more than 60 million green tons of woody biomass feedstock (RISI 2011). Woody biomass from forest residues has long been underutilized due to limited access and high costs associated with collection and transportation (Evans 2008). 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 new industry (Aguilar and Garrett 2009).

Harvesting systems utilizing whole-tree chippers and grinders convert woody biomass into a suitable feedstock for wood energy facilities. A system harvesting roundwood

[1] Center for Forest Business, Warnell School of Forestry and Natural Resources. University of Georgia, Athens, GA 30602-2152, wdgreene@uga.edu

products typically piles logging slash for later collection by a biomass harvesting system using a grinder or chipper. In this paper we compare a range of likely forest biomass harvesting systems, including whole-tree chipping, clean chipping, conventional roundwood, and residue grinding to determine how each system affects woody biomass energy facilities, biomass harvesting firms, and forest landowners.

Literature review

The forest products industry today purchases most raw materials on a green ton basis for convenience and to encourage the delivery of freshly cut wood. Wood energy facilities are likely to prefer drier raw material to maximize energy content. They also often prefer feedstock with a minimum of dirt or grit so that the ash remaining after combustion is reduced. Moisture content and ash content are especially important issues where logging residues such as limbs, tops, and understory stems are collected because moisture and ash affect energy value. Wood energy facilities are also concerned with the elemental or nutrient content of woody biomass feedstocks due to its effect on emissions affecting air quality (Obernberger et al. 1997).

When woody biomass feedstocks will be combusted to provide energy it is advantageous to have low moisture content to increase their energy value (BTU). The heating value of any fuel is the energy released per unit mass or per unit volume of the fuel when the fuel is completely burned (ANSI/ASABE S593.1 2011). Woody biomass has one of the highest energy contents of all biomass sources with over 25 million BTUs per oven-dry ton (Boundy et al. 2011). The moisture content of solid biomass influences the net calorific value and the combustion efficiency (Kristensen and Kofman 2000). Woody biomass products with particle sizes too small or too large negatively influence handling, combustion characteristics, and emissions (Paulrud and Nilsson 2004).

A higher energy value results in greater burning efficiency. 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 lower moisture content than green wood to obtain a higher energy value. The transportation of bioenergy feedstocks has been found to be inherently more costly than fossil fuels because per unit energy density of fossil fuels is two to three times that of biomass (Young 1980). Each 10% reduction in moisture content can increase the net energy content 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 and region – but if allowed to dry for at least four weeks before delimbing and processing, moisture content can be reduced to as little as 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. Loblolly pine (*Pinus taeda*) stems dry at a greater rate with limbs intact than as delimbed stems, they dry more during summer months, and most moisture reduction occurs during the first 30 days of drying (Klepac et al. 2008).

While reducing moisture content is important, keeping ash content low in combustible woody fuels is also vital. Ash is formed from mineral matter during combustion and can cause slagging, which is the coating of internal surfaces in boilers from deposition of ash particles. Ash is a crucial aspect of the concept of sustainable, carbon neutral thermal biomass utilization and may be recycled where appropriate in forests and on agricultural land or put in a landfill (Narodoslawsky and Obernberger 1996).

Woody biomass with higher ash content is considered of poorer quality because it results in poorer combustion performance and increases maintenance and disposal costs caused by glass or slag deposits formed within some burning mechanisms (Sarenbo 2009). The biomass harvesting system employed, the type of woody biomass material, and the manner and duration of how woody biomass is stored and/or piled on-site can all affect moisture and ash content (Obernberger et al. 1997, Pettersson and Nordfjell 2007). Öhman et al. (2004) observed ash content for different types of woody biomass used to make pellets and found that while ash deposits were affected both by burner and feedstock types, stem wood based material produced less ash than bark and logging residues. The wood pelletizing process is less forgiving of ash, as is the burning of woody biomass in stoker grate boilers where slag deposits are prone to form. More technologically advanced circulating fluidized bed boilers tolerate a greater amount of ash than stoker grate boilers (van den Broek et al. 1996).

A number of different biomass harvesting and transportation system configurations that can supply renewable energy facilities already exist, but each operates with a different incoming feedstock (residues, understory, standing trees, etc.), produces a product that differs in its characteristics (moisture content, particle size and uniformity, ash content, etc.), and differs in productivity and costs (Hartsough and Yomogida 1996). Few studies have examined methods that could improve woody biomass characteristics in the field to add value to the feedstock required by bioenergy facilities.

Different approaches for harvesting woody biomass for energy have been studied for decades. Koch (1980) described numerous methods for harvesting biomass, including chipping whole trees at the stump, extracting sawlogs at the landing and processing limbs and tops, chipping residues at a wood consuming mill, and transporting complete boles to a mill for merchandizing. Arola and Miyata (1981) reported on cost and productivity data for five different harvesting methods from conventional logging operations to a land clearing operation for site conversion. A one-pass harvesting system harvests all products concurrently. Harvesting and recovering roundwood and woody biomass are performed in separate passes in a two-pass harvesting system. Watson et al. (1986) compared a conventional harvesting system with one and two pass biomass harvesting systems with the one-pass system having the best utilization and lowest costs.

Cubbage and Greene (1989) compared estimated costs for seven conventional logging systems for a variety of conventional and biomass harvests. Highly mechanized systems using feller-bunchers and grapple skidders were the least costly. Tract size did not greatly influence costs but the study design did not evaluate small harvest blocks. Goulding and Twaddle (1990) studied approaches to improve conventional harvesting methods that lead to increased production of energy wood as a by-product of integrated systems. Economically successful systems were ones where the biomass component was kept attached to conventional products for as long as possible and increased biomass recovery was a consequence of improvements to one or more of the conventional harvesting tasks, i.e. delimbing and bucking.

Puttock (1995) examined two different approaches for estimating costs of producing conventional products and fuel wood with integrated harvesting systems. A marginal cost approach completely allocates the cost of common harvesting activities such as felling, forwarding and processing to conventional products, whereas a joint product approach distributes production costs among conventional products and fuel wood. Production costs are highly variable depending on the type of harvesting employed and the ratio of conventional products to fuel wood.

Patterson et al. (2011) examined five forest biomass collection systems. Two of the systems utilized a chipper, one with thinning material and one with thinning residues. The other three systems utilized horizontal grinders to process roundwood logging residues. The chipping systems produced material with a higher energy content (8,168 vs. 7,785 BTU/lb) and lower ash content (1.2% vs. 4.5%) than the material produced by grinding systems processing roundwood residues.

Methods

We calculated delivered costs per field ton and per million BTU (mmBTU) for seven harvesting systems. We use the term “field” to reference the moisture content of any material at the time of chipping or grinding and use “green” wood to refer to freshly felled wood with the highest moisture content observed in the field. The harvesting systems included: (1) a whole-tree chipping operation producing fuel chips, (2) a clean chipping operation producing pulp quality chips, (3) a horizontal grinding operation processing roundwood logging residues unscreened, (4) a horizontal grinding operation processing and screening roundwood logging residues, (5) a horizontal grinding operation processing clean chipping residues unscreened, (6) a horizontal grinding operation processing and screening clean chipping residues, and (7) a conventional roundwood logging operation.

Physical properties including moisture content, ash content, energy content, and elemental analysis were obtained from Dukes (2012) for screened and unscreened grindings and from Cutshall et al. (in press) for whole-tree chips. Both of these studies collected samples and prepared them for laboratory analyses following the Technical Association of the Pulp and Paper Industry (TAPPI) standard for sampling and preparing wood for analysis (TAPPI 1985). A 6-inch diameter PVC pipe with an elbow was used to collect chip samples and a 5-gallon bucket was used to collect grinding material from each truck load. Small samples were collected several times during the loading of a van and mixed to obtain composite samples. Grab samples (1Kg) from the composite samples were transferred to a kraft paper bag and weighed immediately to determine the field (or wet) weight of the chips or grindings. Each bag was later transferred to a 105℃ oven for a minimum of 24 hou rs and reweighed to determine moisture content. A subsample of bags from each harvesting system were fractioned, processed through a 1 mm screen Wiley mill and transferred to the University of Georgia Plant, Soil, and Water Lab to determine energy, ash, and nutrient content.

Production rates and truck payloads were obtained from Cutshall et al. (in press) and Dukes (2012). Hourly operating costs were calculated using the machine rate approach (Miyata 1980) assuming 85% mechanical availability for all machines in each of the seven harvesting systems. Additional assumptions for all machines included: labor rate of $18.00/SMH; labor fringe/overhead expenses of 40% of the base rate of pay; combined interest, insurance, and taxes of 15% of average annual investment; lubrication costs at 37% of fuel expense; and 2,000 scheduled machine hours per year. We evaluated diesel prices ranging from $3.00 to $6.00 per gallon.

We modified a version of the Auburn Harvesting Analyzer (Tufts et al. 1985) to determine delivered costs for each system. The model was adapted to evaluate a range of values in lab-derived moisture content, ash content, and energy content (BTU per oven dry pound) among whole-tree chipping and grinding systems based on results obtained from Cutshall et al. (in press) and Dukes (2012). For example, whole-tree chips ranged in moisture content from approximately 30% to 55% and ash content varied from approximately 0.5% to 1.0%. Truck payload data from the previous studies were used to obtain ranges in load weights. Trucks transporting whole-tree chips ranged in net weights from 20 to 30 tons, and trucks transporting screened roundwood residue grinding material ranged in net weights from 10 to 20 tons. We added 10% to total costs for a profit margin. Additional variables including tract size, tons removed per acre, tons per landing, truck payload (net tons), and miles of loaded haul distance to the receiving facility were adjusted to determine cost sensitivity.

Delivered costs were calculated by adding a stumpage price of $8.00 per field ton for the RW system and $1.00 per field ton for each grinding system. We assumed the CC system to process 10% less material due to bark and chip sizing losses than the RW system resulting in a stumpage price of $8.89 per field ton and the WTC system to process 25% more material than the RW system resulting in a stumpage price of $6.40 per field ton. To further incorporate biomass costs for wood energy facilities, we added an additional $5.00 per field ton to the RW system to represent the cost of chipping roundwood at a facility. We compared delivered cost per mmBTU data at each variable level using analysis of variance with Tukey's range test used for means comparison (Oehlert 2000).

Results

Estimated delivered costs on an energy basis (mmBTU) for whole-tree chipping and screened and unscreened grinding systems were compared by increasing moisture content (MC) from 30% to 55% (wet basis) (Figure 1). Delivered cost per mmBTU decreased by over 50% for all systems as moisture content decreased from 55% to 30%. The system grinding clean chipping residues without using a screen (GCC) had the lowest estimated delivered costs ranging from $2.68 per mmBTU at 30% MC to

$4.17 at 55% MC. The grinding system processing and screening clean chipping residues (GCC/S) and the system grinding roundwood logging residues without using a screen (GRW) had marginally higher estimated cut and haul costs per mmBTU, respectively, than the GCC system. The whole-tree chipping system had the highest costs of the "economically feasible" systems. Estimated cut and haul costs for the system grinding and screening roundwood logging residues (GRW/S) were by far the highest. This system was not considered to be an economically feasible biomass harvesting option. Dukes (2012) reported that this system averaged 11.7 net tons of truck payload, a 47 minute loading time, and 15.3 tons per productive hour. By comparison, a 780 hp grinder processing and screening clean chip residues averaged 23.5 net tons of truck payload, a 16.9 minute loading time, and 84.7 tons per productive hour.

Ash content, along with moisture content, is a key characteristic affecting net energy content. The whole-tree chipping system produced the lowest estimated delivered cost per mmBTU at the lowest percent ash, $4.39 per mmBTU at 0.5% ash and $4.41 at 1% ash (Table 1). Cutshall et al. (in press) reported ash content of less 0.7% in whole-tree chips. The GCC system produced the lowest estimated delivered cost per mmBTU of $2.87 at 5% ash, but this system also produced loads with high ash content (up to 30%). If target ash content is less than 2%, the WTC system was the lowest delivered cost option followed by the GRW/S system. If 2% ash is acceptable, then the GCC/S system is the lowest delivered cost option at $3.33 per mmBTU. If ash content of up to 10% is acceptable, then the GRW, GCC, or GCC/S systems are options with the lowest costs observed for the GCC system. Delivered costs for the CC and GRW/S systems were not significantly different at α=.05.

Delivered costs per mmBTU for each harvesting system were also compared by increasing net tons of truck payload (Figure 2). The GRW, GCC, and GCC/S systems had the lowest costs for each load size. Costs declined approximately 11% for each system as load size increased except for the GRW/S system which declined 20%. Delivered costs for the GRW and GCC/S systems did not significantly differ at a trucks payload of 15 tons. The GCC and GCC/S systems did not differ at truck payloads of 20, 25 or 30 tons. The GRW and GCC systems and the CC and RW systems did not significantly differ at load sizes of 20 and 30 tons, respectively.

We compared delivered cost per field ton and per mmBTU for each system (Table 2) under likely conditions and with key assumptions more fully described in Cutshall (2012). The GCC system had the lowest delivered cost per field ton and per mmBTU ($22.48 and $2.71, respectively) and the GRW/S system had highest costs at $46.49 and $4.20, respectively. When factoring in moisture and ash content to derive delivered costs on an energy content basis ($/mmBTU), costs per mmBTU for the GRW and WTC-40% (40% moisture content) systems were lowered relative to their cost per field ton equivalent measure. The RW and CC systems were among the costliest based on field tons and mmBTU.

Systems that collect residues behind clean chip or roundwood operations represent a second pass across the site or at minimum a second operation visiting the logging site. When examining these grinding systems from a holistic standpoint, they may not be as favorable due to costs of both passes. Residue collection systems are also limited by the availability of sites that have received a primary harvest first and by definition have less biomass available to collect since higher value products have already been removed in the first harvest pass. In this study the WTC systems produced a relatively costly product, but they had the advantages of requiring a single operation and handling large volumes per acre.

Summary

Delivered costs per unit of energy content associated with harvesting forest biomass for energy production decreased as moisture and ash content decreased. A whole-tree chipping operation was a very suitable harvesting system if wood energy facilities require biomass material to meet an ash content specification of less than 2%. The only grinding system capable of producing material with less than 2% ash was one grinding roundwood logging residue using a screen, but its delivered cost was almost $1.00 per mmBTU higher than that for a whole-tree chipping system due to severely limited truck payloads. The least costly ($2.87 per mmBTU) option where 5% ash content was acceptable was a system grinding clean chipped residue without screening.

Acknowledgments

This study was funded by financial support from the Southeastern SunGrant Center associated with the US Department of Energy and US Department of Agriculture.

Literature cited

Aguilar, F. and H.E. Garrett. 2009. Perspectives of woody biomass for energy: Survey of state foresters, state energy biomass contacts, and National Council of Forestry Association executives. Journal of Forestry 107(6): 297-306.

ANSI/ASABE Standards. 2011. American Society for Agricultural & Biological Engineers, St. Joseph, MI: ASABE S593.1.

Arola, R.A. and E.S. Miyata. 1981. Harvesting wood for energy. US For. Serv. Res. Pap. NC-200. 25p.

Boundy, B., S. Diegel, L. Wright, and S. Davis. 2011. Biomass energy data book: edition 4. Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA.

Cubbage, F.W. and W.D. Greene. 1989. Conventional and biomass harvesting costs by forest tract size. Biomass 20(3-4): 219-228.

Cutshall, J.B., W.D. Greene, and S.A. Baker. In Press. Transpirational drying effects on energy and ash content from whole-tree southern pine plantation chipping operations. Accepted for publication in Southern Journal of Applied Forestry.

Cutshall, J.B. 2012. Options for reducing moisture and ash content in forest biomass harvesting systems. PhD dissertation, University of Georgia, Athens, GA. 82 p.

Dukes, C. 2012. In-wood screening of wood grindings for biomass feedstock applications. M.S. Thesis. The University of Georgia. 44 p.

Evans, A.M. 2008. Synthesis of knowledge from woody biomass removal case studies. Santa Fe, NM. The Forest Guild. 39 p.

Goulding, C.J. and A.A. Twaddle. 1990. Harvesting whole trees with processing and log allocation (in the forest) to conventional and energy products. Biomass 22(1-4): 145-158.

Hartsough, B., D. Yomogida. 1996. Compilation of state-of-the-art mechanization technologies for short-rotation woody crop production. Davis, CA: University of California, Biological and Agriculture Engineering Department. In cooperation with: Electric Power Research Institute; U.S. Department of Agriculture, Forest Service, Southern Research Station. 66 p.

Ince, P.J. 1979. How to estimate recoverable heat energy in wood or bark fuels. USDA For. Serv. Gen. Tech. Rep. FPL 29. Forest Products Lab., Madison, WI. 10 p.

Klepac, J., B. Rummer, and F. Seixas. 2008. Seasonal effects on moisture loss of loblolly pine. Proc. of the 31st Annual Meeting of the Council on Forest Engineering, Charleston, SC, p. 53-61.

Kristensen, E.F. and P.D. Kofman. 2000. Pressure resistance to air flow during ventilation of different types of wood fuel chip. Biomass and Bioenergy 18(3): 175–180.

Koch, P. 1980. Harvesting energy chips from forest residues—Some concepts from the southern pine regions. US For. Serv. Gen. Tech. Rep. CO-33. 25 p.

Miyata, E.S. 1980. Determining fixed and operating costs of logging equipment. USDA Forest Serv. TR-NC-55, North Central Expt. Sta., St. Paul, MN. 14 p.

Narodoslawsky, M. and I**.** Obernberger. 1996. From waste to raw material—the route from biomass to wood ash for cadmium and other heavy metals. Journal of Hazardous Materials 50(2-3): 157-168.

Obernberger, I., F. Biedermann, W. Widmann, and R. Riedl. 1997. Concentrations of inorganic elements in biomass fuels and recovery in the different ash fractions. Biomass and Bioenergy 12(3): 211-224.

Öhman, M., C. Boman, H. Hedman, A. Nordin, and D. Boström. 2004. Slagging tendencies of wood pellet ash during combustion in residential pellet burners. Biomass and Bioenergy 27(6): 585–596.

Oehlert, G.W. 2000. A first course in design and analysis of experiments. W.H. Freeman and Company. New York. 600 p.

Patterson, D, J. Hartley, and M. Pelkki. 2011. Size, moisture content, and British thermal unit value of processed in-woods residues: five case studies. Forest Products Journal 61(4): 316-320.

Paulrud, S. and Nilsson C. 2004. The effects of particle characteristics on emissions from burning wood fuel powder. Fuel 83(7-8): 813-821.

Pettersson, M. and T. Nordfjell. 2007. Fuel quality changes during seasonal storage of compacted logging residues and young trees. Biomass and Bioenergy 31(11-12): 782-792.

Puttock, G.D. 1995. Estimating cost for integrated harvesting and related forest management activities. Biomass and Bioenergy 8(2): 73-79.

RISI. 2011. Wood Biomass Market Report. August 2011. 4(8), 7 p.

Sarenbo, S. 2009. Wood ash dilemma-reduced quality due to poor combustion performance. Biomass and Bioenergy 33(9): 1212-1220.

Stokes, B.J., T.P. McDonald, and T. Kelley. 1993. Transpirational drying and costs for transporting woody biomass – a preliminary review. Proc. IEA/BA Task IX, Aberdeen, UK. 16 p.

TAPPI. 1985. Sampling and preparing wood for analysis. T 257 cm-85. 5 p.

Tufts, R.A., B.L. Lanford, W.D. Greene, and J.O. Burrows. 1985. Auburn harvesting analyzer. The Compiler 3(2): 14–5. Forest Resources Systems Institute, Florence, AL.

van den Broek, R., A. Faaij, and A. van Wijk. 1996. Biomass combustion for power generation. Biomass and Bioenergy 11(4): 271-281.

Watson, W.F., B.J. Stokes, and I.W. Savelle. 1986. Comparisons of two methods of harvesting biomass for energy. Forest Products Journal 36(4): 63-68.

Young, H.E. 1980. Biomass utilization and management implications. Weyerhaeuser Science Symposium 3, Forest-to-Mill Challengers of the Future. Weyerhaeuser. 16 p.

Table 1. Delivered cost estimates ($/mmBTU) by levels of ash content.

	Delivered Cost ($/mmBTU) by Harvesting System				
% Ash	**WTC**	**GRW**	**GRW/S**	**GCC**	**GCC/S**
0.5%	$4.39		$5.27		
1.0%	$4.41		$5.29		
1.5%			$5.32		
2.0%		$3.44	$5.35		$3.33
2.5%			$5.37		
3.0%			$5.40		
4.0%		$3.51			$3.40
5.0%				$2.87	
6.0%		$3.59			$3.47
8.0%		$3.66			$3.55
10.0%		$3.75		$3.03	$3.63
15.0%				$3.20	
20.0%				$3.40	
25.0%				$3.63	
30.0%				$3.89	

Table 2. Ranking (lowest=1) of delivered cost estimates ($/field ton and $/mmBTU) for biomass harvesting systems under likely conditions.

System	**Delivered Cost ($/F-ton)**	**Rank**	**Delivered Cost ($/mmBTU)**	**Rank**
GCC	$22.48	1	$2.71	1
GCC/S	$27.04	2	$3.05	3
GRW	$28.07	3	$2.77	2
WTC-50%	$28.94	4	$3.55	5
WTC-40%	$30.36	5	$3.10	4
RW	$31.07	6	$3.81	6
CC	$31.20	7	$3.82	7
GRW/S	$46.49	8	$4.20	8

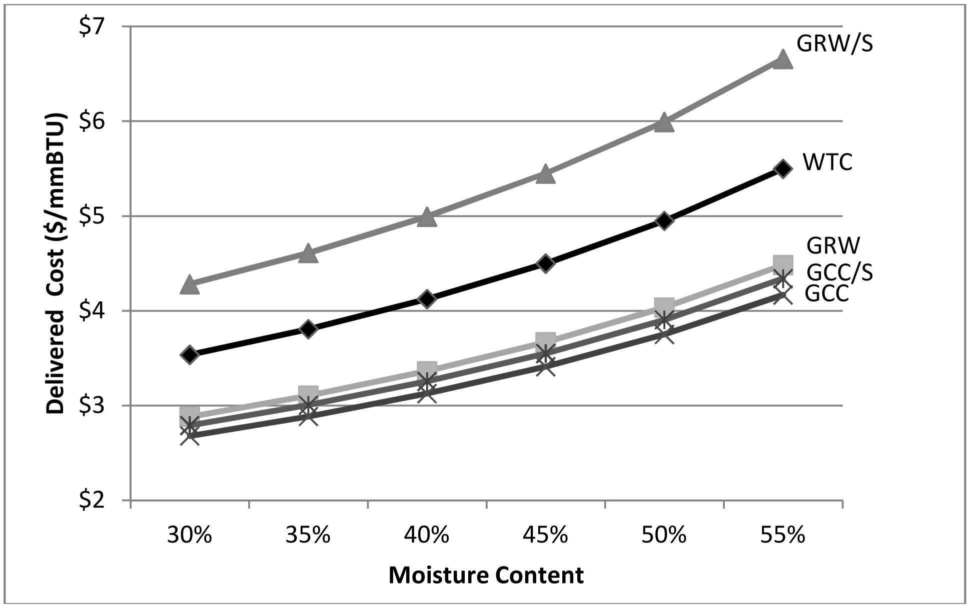


Figure 1. Delivered cost estimates ($/mmBTU) for increasing levels of moisture content.

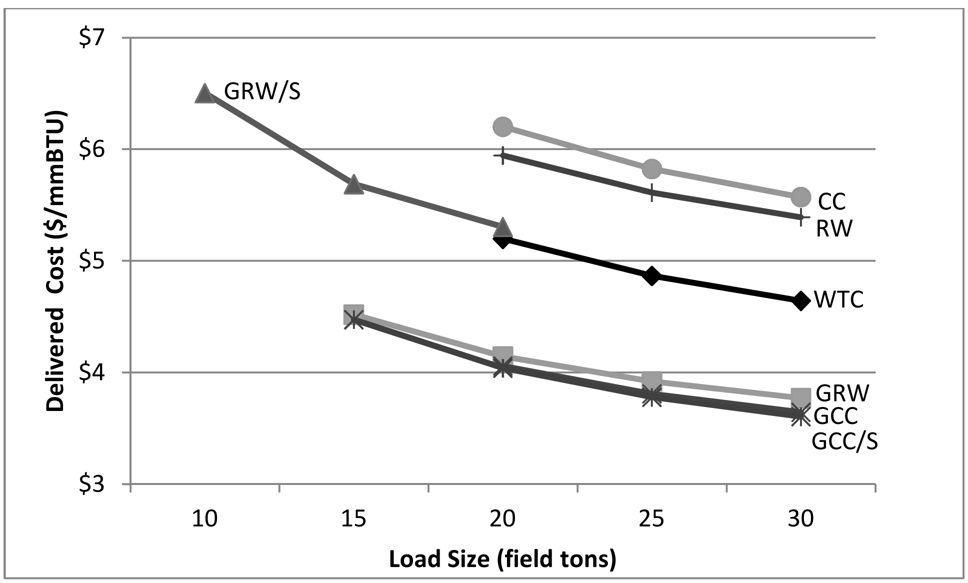


Figure 2. Delivered cost estimates ($/mmBTU) for increasing net tons of truck payload.

ENERGY ANALYSIS OF TWO EUCALYPTUS HARVESTING SYSTEMS IN BRAZIL

Ezer Dias de Oliveira Júnior[1] **and Fernando Seixas**[2]

Summary

Mechanized harvesting of timber is an activity with high investment in machinery, fuel and lubricant, representing an expenditure of energy. The main objective of this study was to analyze the energy consumption in “cut-to-length” and “tree-length” harvesting systems, used in Eucalyptus plantations in Brazilian forest companies. The “cut-to-length” system was composed by a Volvo excavator operating as a harvester machine, and a forwarder Timberjack 1210B. The “tree-length” system module was a feller buncher Timberjack 608L, a clambunk-skidder Timberjack 1710, and one slasher Timberjack 608B.

Operational data and fuel consumption were collected from twenty-two machines, which jointly worked 88,384 hours, producing 7,268,729 m^3 of wood, operating in Eucalyptus plantations located at Southeast part of Brazil (São Paulo and Minas Gerais states). Worksheets calculated the energy expenditure, considering a 7-year old Eucalyptus plantation, with a productivity of 300 $m^3.ha^{-1}$.

The “cut-to-length” system required the investment of 37.8 MJ of energy to harvest one cubic meter of wood. Energy consumed by labor represented only 0.3%, while the machines 6.1% (raw material, manufacture, and maintenance), and fuel consumption 93.6%, representing a total power consumption of 11,340 $MJ.ha^{-1}$. The energy investment in the “tree-length” system was 45.4 $MJ.m^{-3}$. The relative distribution of the consumed energy was 0.2%, 6.1%, and 93.7%, respectively in labor, equipment, and fuel. Considering the production of 300 $m^3.ha^{-1}$, the total energy expenditure was 13,620 $MJ.ha^{-1}$, what made this harvesting system be the largest consumer of energy.

Keywords: Energy analysis, Eucalyptus logging, timber extraction.

Introduction

The Brazil stands out on the world stage because of the importance of forest biomass and its potential with one of the highest rates of forestry productivity, reaching between 40 and 50 cubic meters (m^3) of wood per hectare per year, more than 10 times the observed in temperate countries (STAPE, 2003). Two main mechanized systems are used in forest harvesting in Brazil, developed according to the types of machines and

[1] Professor, Fait/ACITA, Itapeva, SP, Brazil - ezer@fait.edu.br.
[2] Associate Professor, ESALQ/USP, Piracicaba, SP, Brazil – fseixas@usp.br.

handling of wood: the Scandinavian system "cut-to-length", and the North American "tree-length" system (SEIXAS and OLIVEIRA Jr., 2001).
According to Serra et al. (1979), mechanization of operations emphasized the use of fossil energy in increasingly sophisticated ways, as a result of planning and use of machinery, fertilizers and pesticides, providing significant increases in productivity over time. The amount of energy used in the operations depends on several factors, not only the energy from the fuel, but also that aggregated in the manufacture and distribution of machinery, hydraulic and lubricating oil, and labor (BRIDGES and SMITH, 1979; FLUCK, 1985).
Athanassiadis et al. (2002) counted, in terms of fuel consumption, the input energy for timber harvesting of 82 $MJ.m^{-3}$ on Swedish conditions. Of this total, 11% are due to the energy expended in the stage of extraction and refining of fuel. The authors considered that on the energy investment in harvesting activity, 40% were provided by fossil fuel use.
Berg and Lindholm (2004) inventoried the use of energy in forest operations in Sweden between 1996 and 1997, involving all operations, including seedling production, silviculture, harvesting and transport to the main industry. Energy use was 150-200 $MJ.m^{-3}$ of wood depending on the country region. This inventory showed that the energy expenditure of the main transport was higher than that observed in the past decade. In contrast, expenditure at harvest was lower compared to same last period, possibly because of better technology and management.
Damen (2001) estimated for Brazilian conditions, the energy expenditure based on diesel cost per tonne of harvested wood, with values of 1996, focused on the production of eucalyptus for pulp and paper. The energy expenditure for mechanical harvesting, with feller-buncher, skidder and slasher, was approximately 123 $MJ.t^{-1}$. The author considered the cost of harvesting at US$ 8.11 per dry ton of wood, with an estimated energy cost of US$ $1.08.GJ^{-1}$.
The total energy required to perform the activity in each harvesting system will be directly proportional to the number of operations involved, considering the performance and capacity of machines in each module, in addition to the type of machinery used in the modules.
The objective of this study was to analyze the consumption of energy invested in felling operations, prehauling and primary processing in two mechanized harvesting systems, “cut-to-length” and “tree length”, and also identify the most influential factors in each operation, to establish the relationship of energy expenditure on harvesting activities.

Methodology

A matrix was established to calculate the energy expenditure of the mechanized operations in harvest activity in two systems, , “cut-to-length” and “tree-length”, and analyzed according to the demand of energy for its accomplishment, considering an eucalyptus stand producing 300 $m^3.ha^{-1}$ at the end of seven years.

Four forestry companies, working with “tree length” systems, were visited in the years 2003 and 2004, and one company that adopted the “cut-to-length” system, comprising the states of Sao Paulo and Minas Gerais, which were selected in areas with similar conditions of cultivation and an average individual volume of 0.18 m^3 per tree.
The data from operational capacity and fuel consumption represent the performance of eight mechanized modules, totaling twenty-two machines, which jointly worked 88,384 hours, producing 7,268,729 m^3 of wood. The average data of each company considered account for the overall average productivity of machines to harvest one hectare of eucalyptus with similar pattern. The machines were grouped according to Doering (1980) by the power and mass in each harvesting system, obtaining the average overall performance in each module to avoid comparisons of operational capacity among the trademarks or productivity between firms.

Materials

The direct energy was classified in terms of biological power of human labor and fuel. The energy depreciation was considered as indirect energy, because of the power consumption for the machine to be manufactured, being also considered the time spent (hours) and the mass of the machinery used in the operation.

Harvesting description

In both systems the final road side product is 2.20 m logs with bark arranged in the transverse direction. In the “cut-to-length” system considered, the module was composed of a harvester machine Volvo excavator based and one Timberjack 1210B forwarder. In the “tree length” system, the module was one feller buncher Timberjack 608L, one clambunk-skidder Timberjack 1710, and one slasher Timberjack 608B.

Methods

In this analysis, the energy inputs were classified and quantified according to the source, considering the characteristics of the machines, operational performance (machines and workforce), and fuel consumption in each forest enterprise activity.
In matrix calculation, the energy inputs were organized in the vector called "entries vector", which corresponds to the energy intensities of each energy flow. The operating time ($h.ha^{-1}$) and fuel consumption ($L.ha^{-1}$) were organized in the matrix called "consumption matrix", according to Sartori and Basta (1999). Multiplying the input vector by the energy consumption matrix resulted in a vector with the values of energy expenditure in each activity expressed in units of energy per cubic meter or per hectare ($J.m^{-3}$ or $J.ha^{-1}$).
The machines used in each harvesting system were depreciated in terms of added energy, accounting the used raw material, energy consumed in manufacturing, with repairs and maintenance throughout life. Machine annual use, its mass and power were considered in calculations, according to the methodology proposed by Doering (1980) (Equation 1).

$$E_{RM} = (E_{MM} + E_{IM}) \times m \times 0.333 \times RM / L_U \qquad (1)$$

where:

E_{RM} = energy spent on repairs and maintenance ($MJ.h^{-1}$);

E_{MM} = energy value used to machine manufacturing: 14.6 $MJ.kg^{-1}$;

E_{IM} = energy value of the incorporated material: 50.0 $MJ.kg^{-1}$;

m = machine mass (kg);

L_U = useful life (h);

RM = coefficient for repairs and maintenance (0.74).

The energy spent by hour for machine manufacturing and incorporated material was calculated multiplying the energy value ($MJ.kg^{-1}$) by machine mass, and dividing the result by 82% of the useful life in hours (L_U = 5 years x 6,000 $hours.year^{-1}$ = 30,000 hours), being 18% considered as a residual life.

Results

The results of machine operational capacity are presented in Table 1, with those results being utilized for the energy calculation. The results of energy calculations presented in Table 2 show that the higher powered machines had higher aggregate energy per hour, mainly due to the mass. This difference in energy depreciation data was considered in the energy inputs used in the calculations.

Matrix calculation of harvesting activities

The entries vector and consumption matrix are shown in Figure 1. The answer vector indicates the energy expenditure per type of machine used, and the sum of these values resulted on the final value of each module. The values express the expenditure of energy to handle a cubic meter of wood. The sum of the values in answer vector (Figure 1) resulted in the expenditures of energy in each system under study, as shown in Figure 2.

Table 1. Operational capacity and fuel consumption of machines in each harvesting system.

System	Operation	Machine	P ($m^3.h^{-1}$)	Diesel ($L.m^{-3}$)
Cut-to-length	Harvesting	Harvester	35.4	0.53
	Forwarding	Forwarder	42.8	0.40
Tree-length	Felling	Feller bunch	74.9	0.39
	Skidding	Clambunk	55.5	0.40
	Bucking	Slasher	57.0	0.33

P = machine productivity.

Table 2. Energy depreciation of logging machines.

Machine	Mass (t)	Powe (kW)	Useful Li (h)	E_{IM} (MJ.h	E_{MM} ($MJ.h^{-1}$)	(E_{IM}+E_{MM}) x 0.82 ($MJ.h^{-1}$)	E_{RM} ($MJ.h^{-1}$)	Total ($MJ.h^{-1}$)
Harvester	19.5	160	30,000	32.7	9.5	34.6	10.4	45.0
Forwarder	19.5	160	30,000	32.7	9.5	34.6	40.4	45.0
Feller	27.2	180	30,000	45.5	13.2	48.2	14.5	62.7
Skidder	19.5	160	30,000	32.7	9.5	34.6	10.4	45.0
Slasher	27.1	180	30,000	44.8	13.2	47.6	14.3	61.9

E_{IM} = Added energy in raw materials; E_{MM} = Added energy in manufacturing; E_{RM} = Energy spent with repairs and maintenance.

Entries vector x Consumption matrix = Response vector

	Workforce ($MJ.h^{-1}$)	Machine 1 ($MJ.h^{-1}$)	Machine 2 ($MJ.h^{-1}$)	Diesel ($MJ.L^{-1}$)	
Entries vector	2.2	45	62	38	
Workforce ($h.m^{-3}$)	0.028	0.023	0.013	0.018	0.018
Machine 160 kW ($h.m^{-3}$)	0.028	0.023	0.000	0.018	0.000
Machine 180 kW ($h.m^{-3}$)	0.000	0.000	0.013	0.000	0.018
Diesel ($L.m^{-3}$)	0.53	0.40	0.39	0.40	0.33
	Harvester	Forwarder	Feller	Skidder	Slasher
Response vector ($MJ.m^{-3}$)	21.46	16.30	15.65	16.05	13.70

Figure 1. Matrix calculation of energy expenditure on harvesting activities.

The "tree-length" system presented power consumption approximately 20% higher when compared to the "cut-to-length" system. Considering the higher calorific value of wood equal to 19 $GJ.t^{-1}$, the harvest energy investment is about 0.5% of the energy potential from the eucalyptus plantation.

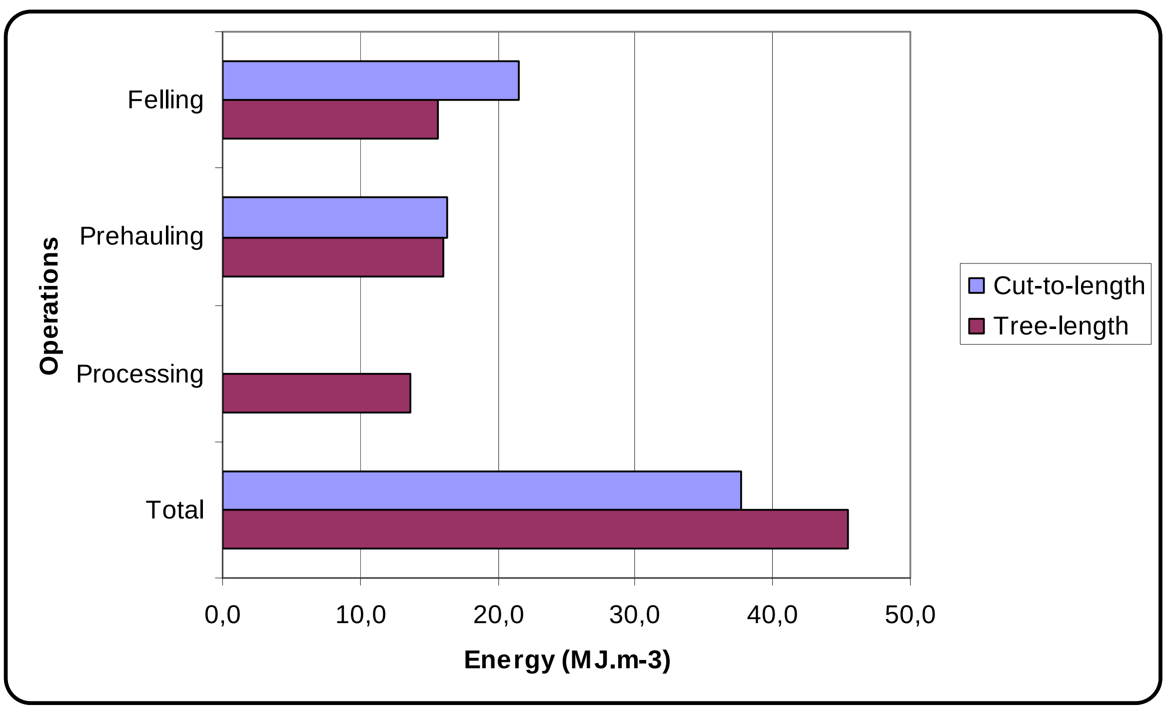


Figure 2. Final energy expenditure at each operational system.

Discussion

The higher power consumption in both systems was due to fuel consumption, 93.7% of the total. Lower demand was required by human labor, 0.2% of the total, indicating, of course, that labor is not a limiting factor in terms of energy. Energy depreciation took an average of 6.1% of the total for the two systems, and was not associated to the machine power, but to the machine mass, according to the method as proposed by Doering (1980), indicating that further repairs and maintenance were not of great expenditure of energy.

There was an influence of machine size and power on energy consumption, as verified by Bridges and Smith (1979). The harvester work, felling and processing trees, was responsible for 56.8% of energy demand, being forwarding the remaining 43.2%. In the "tree-length" system, felling and processing trees, made by feller buncher and slasher, required 64.7% of total energy and the remaining 35.3% was used by the skidder. There was a better distribution of the power demand on the first system, while the "tree-length" system has a concentrated demand of energy in the felling and processing operations.

The machine productivity was the most important factor to the energy consumption, with the "tree-length" system being more productive. It is suggested to study the influence of increased carrying capacity of the forwarder, as a way to increase its energy efficiency.

The matrix calculation was effective, but the level of details of the required inputs for the desired operation must be carefully considered. It is evident on this type of analysis, the possibility of the use of environmental indicators (energy efficiency) in the selection of mechanized systems to be adopted by the company, and also to monitor the impacts of outsourcing operations.

Conclusions

The higher demand was fuel consumption in both harvesting systems, around 94% of total energy investment. Felling and processing were the greater energy demand on logging operations, with a higher concentration on "tree length" system because the necessity of two machines instead of one single harvester used on "cut-to-length" system.

The most important factors were: fuel consumption, weight and number of machines, and the operational performance of the harvesting module. The largest number of machines and greater mass implies greater energy expenditure, which must be considered when choosing a harvesting system. The harvest of logs by the "tree-length" system had energy consumption 20% higher compared to the "cut-to-length" system.

From a technological standpoint, the energy invested in operations was proportional in the two systems, but in terms of energy efficiency, in relation to the flows of inputs and outputs, the energy investment in the "cut-to-length" equals 0.40% of the energy produced by eucalyptus plantation, and the "tree-length" system 0.48%. This difference corresponds to the energy equivalent of 60 liters of diesel oil per harvested hectare, which becomes relevant when considering the total volume of wood moved annually by companies.

Each company must evaluate the energy consumption in their specific operating conditions, in order to complement the decision-making and its implications in the long-term energy availability.

References

BRIDGES, T.C.; SMITH, E.M. A method for determining the total energy input for agricultural practices. Transactions of the ASAE, St. Joseph, v.22. p.781–784, 1979.

DAMEN, K. Future prospects for biofuel production in Brazil: a chain analysis comparison of ethanol from sugarcane and methanol from Eucalyptus in São Paulo State. Utrecht: Copernicus Institute for Sustainable Development and Innovation. Department of Science Technology and Society, 2001. 68p.

DOERING, O.C. Accounting for energy in farm machinery and buildings. In: PIMENTEL, D. (Ed.) Handbook of energy utilization in agriculture. Boca Raton: CRC Press, 1980. 475p.

FLUCK, R.C. Energy sequestered in repairs and maintenance of agricultural machinery. Transactions of the ASAE, St. Joseph, v.28, n.3, p.738–744, 1985.

SARTORI, M.M.P.; BASTA, C. Métodos matemáticos para o cálculo energético da produção de cana de açúcar. Energia na Agricultura, Piracicaba, v.14, n.1, p.52-68, 1999.

SEIXAS, F.; OLIVEIRA JÚNIOR, E.D. Compactação do solo devido ao tráfego de máquinas de colheita de madeira. Scientia Forestalis, Piracicaba, n.60, p.73–87, 2001.

SERRA, G.E.; HEEZEN, A.M.; MOREIRA, J.R.; GOLDEMBERG, J. Avaliação da energia investida na fase agrícola de algumas culturas: relatório final. Brasília: Ministério da Indústria e Comércio. Secretaria de Tecnologia Industrial, 1979. 86p.

STAPE, J.L. Pesquisa busca maior retorno das áreas de reflorestamento. Disponível em: <http://www.ipef.br/servicos/clipping/007-2003.html>. Acesso: 26/02/2003.

Acknowledgment

The authors thank the companies, Cenibra, Duratex, International Paper, and VCP, to their support to this research. They also thank the “Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – CAPES” for financial support and scholarship.

IN-WOODS SCREENING OF GRINDINGS FROM LOGGING RESIDUES TO IMPROVE BIOMASS FEEDSTOCK QUALITY

(poster)

C. Cory Dukes[1], W. Dale Greene[2] and Shawn A. Baker[3]

Abstract

Logging residues present a substantial near term opportunity as a bioenergy feedstock, but contaminants can be introduced during collection that potentially increase ash content and/or reduce energy content. We studied the use of a trommel screen to reduce ash levels in ground forest harvest residues at time of production by screening out fines. Eight treatments of initial harvest type (roundwood or clean chip), grinder size, debris age (4 or 8 weeks), and screen usage were applied to southern pine plantation residues in the coastal plain of South Carolina. Use of the trammel screen reduced average ash levels of screened roundwood and clean chipped debris from 4.0% to 1.4% and from 11.9% to 6%, respectively, compared to grinding without screening. Average energy content per unit of oven-dry weight did not significantly improve with screening. Use of the screen reduced utilization of the large grinder from 58% to 47% when processing roundwood residues. From a cost perspective, screened roundwood residues were consistently more costly to produce than either unscreened roundwood or screened clean chipped debris with either grinder size under a number of economic and operational scenarios. Screening roundwood residues after grinding did not appear economically justified given the reduced production and lower truck payloads due to low density material produced. Financially, the screened clean chip systems and the unscreened roundwood material provided the most competitive residue on an energy basis.

[1] Former Graduate Student
[2] Professor, Warnell School of Forestry and Natural Resources. University of Georgia. Athens, GA, USA 30602-2152.wdgreene@uga.edu
[3] Research Professional Center for Forest Business. Warnell School of Forestry & Natural Resources. University of Georgia. Athens, GA 30602-2152. shbaker3@uga.edu

Fecon Woody Biomass Harvesting Solutions

Dennis Goldbach[1]

Abstract

FECON Manufacturing has long specialized in mulching and biomass harvesting machinery. Our major products include the Bull Hog brush cutting heads, tree shears, stump grinders, track mulchers, drilling equipment and woody biomass harvesting machines. In this presentation we focus on Bioharvesting products and systems that have evolved from Fecon mulching and grinding technologies specifically we will feature the Pick-Up Mulcher and Chipper Forwarder machine systems.

The Fecon® **Bio-Harvester**™ is a unique piece of forestry equipment which simultaneously fells, chips, and collects biomass. The material is chipped using Fecon® chipper knives or carbide tools, it is then augured into a material fan and blown into various types of collection units. The harvesting head is mounted on a Fecon FTX440 crawler mulcher or large agricultural tractor (minimum 250 horse power). The FTX440 has the ability to withstand forest conditions and tow a collection unit. The Bio-Harvester™ enables utilization of hazardous forest fuel loads, habitat restoration materials and plantation thinning residues; providing a non-agricultural renewable energy biomass supply. The Bio-Harvester™ targets material 6" in diameter and smaller. The harvester produces green forest chips from previously unutilized and fire-prone ladder fuel material. The chips can then be used to produce bio-energy via the generation of electricity or liquid fuel production. The Bio-Harvester™ is continuing to be tested in various applications to increase productivity and provide a commercially competitive biomass harvesting system. The Fecon Bio-Harvester™ will be a vital tool as the United States works to economically increase usage of renewable energy.

Fecon's® **RTC22** is a purpose built mobile chipping system like no other. This dedicated carrier is specifically designed for chipper weight, center of gravity, and serviceability. The high mobility of the RTC22 is welcomed on remote jobsites that could be hard to get to with other vehicles. With a top speed of 12 miles per hour, the RTC22 is three times faster to the job.

The power of our standard hydraulic infeed table, easily handles small branches and slash and whole trees up to 22" in diameter. The optional Whole Tree infeed produces over 16,000 lbs of limb crushing torque. Both infeed styles feature Fecon's Power Feed Management infeed system. The RTC22 is well suited for a number of other applications. With Fecon's optional felling grapple saw we have made it possible for one piece of equipment to do the work typically done by feller bunchers, excavators, and chippers or grinders. The rubber tired design is a great benefit to any roadside chipping operation. The RTC22 can travel on pavement with no damage to the surface of the road and reach into ditches to remove and chip wood waste. Right-of-way operations

[1] FECON

benefit from the high travel speeds and reduced trimming needed with the extreme crushing capacity of Fecon's Power Feed Management.

Available on three different carrier models to help better customize to customers needs, the RTC22 comes in 4, 6, and 8 wheel models ranging from 148hp to 300hp.

ThinTool: A spreadsheet model to evaluate fuel reduction thinning cost, biomass for energy, and nutrient removal

Sang-Kyun Han[1], Han-Sup Han[2], William J. Elliot[3], William R. Coltrin[4] and Bruce R. Hartsough[5]

Abstract

Mechanical fuel reduction thinning including biomass removal is expensive, creates opportunity for biomass energy, and removes nutrients from the site. Forest managers could use a comprehensive tool to effectively and simultaneously address these aspects of fuel reduction thinning projects. We developed a spreadsheet-based model, named ThinTool, to evaluate the cost of mechanical fuel reduction thinning treatments including biomass removal, predict net energy output, and assess nutrient impacts in northern California and southern Oregon. A combination of literature review, field-based studies, and contractor surveys were used to develop this model. Three components (cost, energy output, and nutrient removal) in ThinTool were directly linked to each other. The results are sensitive to stand and site conditions, thinning prescriptions, biomass recovery systems, and road standards and distances. For cost analysis, machine productivities for fuel reduction thinning treatments under three different stand conditions were obtained from 29 local contractors who have worked on fuel reduction thinning treatments in the region. These estimates are then adjusted based on stand variables and work conditions; the productivity adjustment functions were developed for four key variables affecting machine productivity, including the amount of volume to be removed per acre, tree size, percent slope, and skidding distances. Net energy output was estimated by comparing the amount of energy delivered with the total energy consumed to collect, process, and transport the biomass to an energy plant. This function allows users to assess potential energy contribution and identify energy-effective biomass recovery systems. The site nutrient removals were calculated based on the biomass amounts and nutrient contents for each species and the tree components (e.g., limbs, tops, and/or bole wood) to be removed. The outputs help forest managers to examine environmental effects of biomass recovery and provide nutrient retention information for sustainable production of woody biomass. In model validation, the difference between ThinTool-simulated costs and the actual observed costs were 5 percent for sawlog production and 11 percent for biomass production. ThinTool will help forest managers and land owners to effectively address conflicting issues (i.e. nutrient recycling vs. removal of hazardous fuels) that require integration of biomass availability, harvest cost analysis, and environmental effects simultaneously.

[1] Research Associate, Department of Forestry & Wildland Resources, Humboldt State University, Arcata,California.
[2] Professor, Department of Forestry and Wildland Resources, Humboldt State University, Arcata, California.
[3] Research Engineer, Rocky Mountain Research Station, USDA Forest Service, Moscow, Idaho.
[4] Research Associate, Department of Forestry & Wildland Resources, Humboldt State University, Arcata,California.
[5] Professor, Department of Biological and Agricultural Engineering, University of California, Davis, California.

Keywords: mechanical fuel reduction thinning, forest biomass, costing model, nutrient recycling.

Introduction

Treatments to reduce hazardous fuel accumulations often involve mechanical thinning because mechanical treatment effectively addresses high levels of fuel connectivity in high density stands and allows the subsequent use of prescribed burning with reduced complexity. Federal land managers have identified 73 million acres of National Forest lands in the western U.S. that are characterized as having unnatural or excessive amounts of woody vegetation, leaving these areas prone to catastrophic wildfires (USDA Forest Service 2003). Forest residues generated from thinning overstocked forest stands and traditional timber harvesting operations creates an opportunity for energy generation.

Mechanical fuels treatments use equipment to fell, skid or yard, and process the materials to be removed. The economics of mechanical fuel reduction thinning to reduce wildland fire hazard is often questioned by forestland managers when evaluating the practicality of thinning projects. However, there has been lack of models to accurately predict costs of fuel reduction thinning treatments. A modeling technique that synthesizes past biomass studies and automatically selects useful information for site-specific application can effectively address local conditions when estimating harvesting productivity and costs (Pan et al. 2008b). Few machine productivity and cost estimate models have been developed for small-diameter tree harvesting and mechanical fuel reduction thinning in the western United States. STHarvest (Hartsough et al. 2001) was developed to estimate the cost of harvesting small diameter trees using productivities developed from a large number of past studies. A revised version, FRCS (Fight et al. 2006), was developed to include more aspects of fuel reduction treatments. Lowell et al. (2008) also developed a harvest cost-revenue (HCR) estimator to estimate harvest costs and raw log values of wildfire fuel reduction treatments in the southwestern United States. However, this model was driven by production equations from only one case study that was conducted in a ponderosa pine stand in northern Arizona.

In fuel reduction thinning, mechanical harvesting of forest biomass for energy also raises questions about the net energy contribution due to the use of fossil fuel. A net energy analysis is often performed to investigate the net energy ratio comparing the amount of energy delivered to society by a technology with the total energy consumed to harvest, extract, process, transport, and comminute for energy production. Adams (1983) found that net energy ratios ranged from 18.2 to 25.0 in small wood harvesting using a cable system (stump to truck). Pan et al. (2008a) estimated the net energy generated from mechanical fuel reduction thinning treatments using a ground-based system on pure ponderosa pine stand in Arizona. They reported the net energy ratio was 10.4. These past studies also found that the net energy contribution of fuel reduction thinning was significantly associated with hauling distance to the market because energy used for hauling biomass represented the largest part (36%) of the total input energy. In addition, tree size had a direct effect on net energy ratio. Harvesting larger size trees should generally improve the net energy ratio by increasing machine productivity.

Another limitation in biomass harvesting studies is the lack of integration between woody biomass removal and the environmental effects of these operations. Removal of woody biomass including small whole trees, limbs, and tops can remove on-site nutrients at a greater rate than harvesting stem wood only in traditional logging. In many forest stands, whole-tree harvesting depleted some nutrients, while in others such harvesting had little or no effect on total ecosystem nutrients (Mann et al. 1988). In addition, the impacts of stand removal on site productivity varied with soil type, tree species, and ecosystem or climatic regime (Grigal and Vance 2000). Although several past studies stated that loss of nutrients from fuel reduction thinning could have negligible short-term impacts on the site, it is still important to quantify the amount of nutrient loss from fuel reduction treatments to monitor the impact of thinning operations on long-term stand productivity.

The objective of this research is to develop a spreadsheet-based comprehensive model that allows forest practitioners to 1) accurately predict the cost of fuel reduction thinning treatment using ground-based systems, 2) estimate energy contribution, and 3) assess the impacts on soil nutrients of fuel-reduction thinning treatments in northern California and southern Oregon. We also conducted a field-based validation of the model to evaluate how accurately it estimates fuel reduction thinning costs.

Methods

Using a combination of literature review, field-based studies, and a contractor survey, we developed a spreadsheet-based fuel reduction cost model, named ThinTool, which incorporates net energy output and nutrient impacts on fuel reduction thinning sites in northern California and southern Oregon. The model was developed using Microsoft Excel in conjunction with Visual Basic for Applications (VBA). Three components – cost, energy output, and nutrient removal – are directly linked to each other and realistically respond to changes in thinning prescriptions (e.g., thinning intensity and species selection) and operations requirements (e.g., skidding distance and machine size) (Fig. 1).

2.1. Predictive cost model development

2.1.1 Volume estimation

ThinTool is a stand level thinning production and cost prediction model. Production and cost estimates are based upon specific thinning prescriptions and stand conditions, including current standing tree volume, merchantable and biomass tree volume removed, diameter breast height (DBH), slope, and total harvest area. Height-diameter equations developed by Vitorelo (2011) were used to estimate tree height. Species-specific regional tree biomass equations (Zhou and Hemstrom 2010) developed in the Pacific Northwest were used to predict current standing tree volume and sawlog volume (cubic-foot volume) from 1-ft stump to a 4- or 6-inch top. Biomass weight of tree components (e.g. stem, bark, branches, and foliage) was estimated using biomass equations developed by Jenkins et al. (2003). These estimated sawlog volumes and biomass amounts were also used to calculate net energy outputs and site nutrient removals.

2.1.2. Harvesting system and machine cost

Harvesting system and machine type vary with thinning treatment regions and stand conditions. To representatively estimate thinning costs in ThinTool, one representative machine type for each operation was selected through literature review and personal communication with logging contractors working in northern California and southern Oregon. Whole-tree harvesting method using a ground-based system was implemented for fuel reduction thinning in the model because it is current popular harvesting method to effectively reduce fuel loading and recovery forest residues for energy production from sites. Machine cost information was collected from past studies developed in northern California and southern Oregon (Vitorelo 2011). Chippers, grinders, and bundlers can be selected to process forest residues that can be used for fuel in various power-generation plants. The model classified the chippers into two major categories (i.e. small: ≤500 horsepower (hp) and large: >900 hp) by their horsepower. Grinders were classified into three different categories (i.e. small: <500 hp, medium: 500 – 900 hp, and large: >900 hp). Two different biomass operation logistics (i.e. processing at landing vs. centralized biomass processing) and three different pre-hauling options (modified dump trucks, hook-lift truck, and log truck) were included in the model. In addition there are two different biomass loading options: hot operation and cold operation.

2.1.3. Machine productivity estimation

A new approach was applied in ThinTool to accurately predict fuel reduction thinning costs on a wide range of local site conditions in southern Oregon and northern California, The first step to this approach was to identify key independent variables affecting machine productivity through a literature review on published papers describing harvesting productivity and cost.

The second step to this approach was to obtain representative machine productivities for sawlog and biomass extraction in mechanical fuel reduction thinning through expert opinion surveys. Based on key independent variables identified from the literature review, three “typical” stand conditions that are often treated for fire hazard reduction in this region were developed for this survey. Each stand consisted of mixed conifers with an average sawlog size of 13” DBH. The variable that changed for each stand scenario was the volume of sawlog removal, which was 4 MBF, 7 MBF, and 10 MBF sawlog removals per acre with biomass removal of 7 green tons (GT) per acre, in order to find the effect of this variable on machine productivity. Average ground slope and skidding distance were assigned into 15 percent and 400 feet, respectively.

The final step was to develop adjustment factors that adjust representative machine productivity, in order to accommodate a wide range of site variables found in the first step, such as average tree size, slope, and skidding distances. Time and motion studies conducted in southern Oregon and northern California allowed us to perform various sensitivity analyses to develop adjustment factors in estimating thinning operation productivity that accurately reflect stand conditions and thinning operations requirements.

2.2 Net energy output

Net energy output was estimated in the model by comparing the amount of energy generated with the total energy consumed from stumps to energy plants to produce the biomass energy. The amount of diesel used by each machine was determined from machine productive time, specific fuel consumption rate, and engine horsepower. The total diesel consumption amounts were converted to an equivalent heating value (British thermal unit, BTU) as the total energy input. The energy content was taken at 139,200 BTUs per gallon for diesel, and 125,000 BTUs per gallon for gasoline (Adams 1983).

Recoverable energy output was based on the amount of harvested woody biomass, moisture content and species. Energy output was defined as the total recoverable heating value from the produced forest residues and was calculated using the following formula (Ince 1979):

$$RHV = HHV \cdot (1 - MC_{wb}) - HL$$

Where:

RHV = recoverable heating value, BTUs/pound
HHV = higher heating value, or the maximum potential energy in dry forest residues, BTUs/pound
MC_{wb} = wet-based moisture content, percent
HL = heat loss, BTUs/Pound

Heat loss was estimated under the following assumptions (Ince 1979): the combustion heat recovery system was operated with 40 percent excess air and a stack gas temperature of 500 ℉, which is typical for an indu strial system the ambient temperature of hog fuel before combustion (room temperature) was 68 ℉; the constant conventional heat loss factor was 4 percent and the hog fuel had complete combustion.

2.3 Site nutrient removal

The site nutrient removals are calculated based on the biomass amounts and nutrient (i.e. N, P, K, Ca, and Mg) concentrations for each species and tree biomass component (i.e. stem, bark, limbs, and foliage) removed. Nutrient contents for each species and tree biomass component were collected from past studies conducted in northern California and southern Oregon (Ranger et al. 1995; Pearson et al. 1987).

2.4 Model validation

Model validation involves the process of evaluating how accurately it estimates fuel reduction thinning treatment costs and an overall economics for any given harvesting system and biomass processing option. Past fuel reduction thinning studies conducted in northern California and southern Oregon were used to validate the model (Vitorelo 2011). Stand information from those studies were input to the model and the model-predicted results were compared with the reported results. Any statistical analysis between model estimates and reported results was not developed in this paper because only one past study is available to use model validation. Therefore, further validation work will be accomplished using future fuel reduction thinning projects in northern California and southern Oregon

2.5 Statistical analysis

Statistical analysis for data obtained from expert opinion surveys was performed using SAS 9.2 program (SAS Institute Inc. 2003). Machine productivity data were sorted by each harvesting system and each machine and then average machine productivity was calculated. The effect of sawlog volume to be removed on machine productivity was tested using one-way analysis of variance (ANOVA) in each machine operation (i.e. felling, skidding/yarding, processing, and loading), separately. The significance level were set to 5% (α = 0.05).

Result and discussion

3.1. Machine productivity and cost estimation

The most critical part in the cost model development was how to accurately predict machine productivity and cost at a certain stand condition and harvesting system. There are numerous approaches (expert opinion method, transaction evidence method, accounting method, and engineering cost analysis) for estimating machine productivity. Expert opinion method and engineering cost analysis were combined to estimate machine productivity in this model.

In ground-based systems, tree size (DBH) and slope were considered as key independent variables for a feller-buncher, while key variables for a skidder were skidding distance and slope. Only tree size was identified as a key variable affecting processor productivity. In addition, the amount of volume to be removed was identified as the most significant factor affecting machine productivity in ground-based harvesting systems, although this variable was not included in prediction equations (Johnson 1988; Lowell et al. 2008; Bolding et al. 2009).

A logging contractor survey was conducted to obtain representative machine productivities for mechanical fuel reduction thinning treatments on three different stand conditions (4 MBF, 7 MBF, and 10 MBF sawlog removals per acre). Representative machine productivities for sawlog and biomass removals are presented in Tables 1 and 2. In both sawlog and biomass removal operations, representative machine productivity increased as volume per acre of removal increased. The only operation that significantly differed between treatments was felling ($p = 0.0154$, Table 1). Therefore, felling costs in fuel reduction thinning treatments can be significantly reduced by increasing the sawlog volume. Keegan et al. (2002) also found that travel time between trees marked for removal was reduced with increasing sawlog volume of removal and resulted in increased feller-buncher productivity. In ground-based biomass removal, machine productivities for both feller-buncher and skidder operations tended to increase with an increase in sawlog volume removed, but it was not significant ($p = 0.9349$ for feller-buncher; $p = 0.3445$ for skidder; Table 2). Feller-buncher productivity was higher than skidder productivity. Average machine productivity for feller-buncher ranged from 36 to 39 GT/productive machine hour (PMH).

Adjustment factors were developed to adjust representative machine productivity determined from logging contractor surveys, in order to accommodate a wide range of site variables identified from literature reviews, such as average tree size, slope, and skidding distances. Adjustment factors developed from case studies are presented in Fig. 2. In feller-buncher operation, larger trees had higher percent increments in adjustment factor values. This means feller-buncher productivity increased with increase tree size for sawlog production. However, the adjustment factor value was not highly changed with changing percent slope, although slope was found as one of the key variables affecting machine productivity from literature reviews. Slope had an effect on machine productivity with the skidder. Skidder productivity increased with a decrease in slope. In addition skidder productivity was reduced with an increase in skidding distances.

3.2. Model validation

Model validation for ThinTool was conducted to evaluate how accurately it estimates hazardous fuel reduction thinning treatment costs for any given harvesting system. In model validation, simulated harvesting costs estimated by ThinTool were compared to actual harvesting cost developed from a time-motion study that was conducted at Klamath National Forest near Yreka, California.

The model validation procedures showed that sawlog harvesting costs simulated by ThinTool were higher than harvesting costs estimated by the actual time-motion study (Table 3). The difference between actual and simulated harvesting costs was 5 percent. In biomass production, actual biomass harvesting costs were higher by 11 percent than simulated biomass harvesting cost. Although the current cost model produced overestimated harvesting costs for sawlog production and underestimated harvesting costs for biomass production, it was difficult to evaluate the accuracy of the current model because one case study was used in model validation. Therefore, further validation works is needed to improve model accuracy using future fuel reduction thinning projects.

3.3. Net energy output

A model simulation for net energy output was conducted using a case study scenario used in cost model validation. The case study site totaled 25 acres and was stocked with Douglas-fir (*Pseudotsuga menziesii*), white-fir (*Abies concolor)*, ponderosa pine *(Pinus ponderosa)*, sugar pine *(Pinus lambertiana)*, and incense-cedar *(Calocedrus decurrens)*. Biomass volume removed was 31.3 GT/acre at 55 % moisture content. Harvesting method was whole-tree harvesting. The one-way hauling distance to a plant was 55 miles. Indirect fuel consumption such as moving equipment and crew transportation was not applied in this simulation. Total direct diesel consumption was 1,544 gallons for the harvesting system, equivalent to 215 MMBTUs (million BTUs; Table 5). Truck hauling was the largest direct energy input component (61.9%) because it had the longest operation time with a relatively high-horsepower engine. Pan et al. (2008) reported the similar results that hauling consumed 48.0 percent of the direct input energy at 33 miles one-way traveling distances. The higher hauling energy input in our simulation was contributed by longer one-way travel distance (45 miles). These high energy consumption percentages in hauling operation support the importance of biomass recovery operations close to markets. In addition, reducing moisture content for forest residues before hauling should significantly increase transportation efficiency and reduce total hauling energy input. The grinder consumed 23.4 percent of the total direct input energy, reflecting the large engine size (>900 hp) of machine and the highest diesel consumption rate (gal/hr, Table 5). The feller-bencher work independently and consumed had a higher fuel consumption than skidder due to higher fuel consumption rate.

In this simulation, the total recoverable energy output was 3,245 MMBTUs. Subtracting the energy input, the net energy output was determined to be 3,030 MMBTUs. The net energy ratio between the recoverable energy output and the fossil fuel energy input was 15.1. Pan et al. (2008a) reported the net energy ratio of 10.4 for harvesting ponderosa pine trees less than 5 inches in DBH using mechanized whole-tree system. The net energy ratio would have been 11.4 if indirect energy input was excluded. In our simulation, higher net energy ratio was influenced by higher production rates in harvesting small trees and logging residues generated by sawlog harvesting operations that were not included in net energy output estimation.

3.4. Site nutrient removal

All forest management activities often have impacts on site nutrient budgets in both the short and long term. Therefore, assessing potential impacts of forest residue removals is important for balancing residue removal with retention to ensure site productivity. ThinTool can allow users to effectively estimate site nutrient removal in different harvesting systems, stand conditions, and thinning prescriptions.

In our study, site nutrient removal was estimated using a case study conducted in cost model validation and net energy output simulation. The amounts of nutrient removed from sites by fuel thinning treatments were presented in Table 6. The greatest nutrient removal was found in Calcium (Ca). A similar result was found by Mann et al. (1988) that conducted site nutrient removals by whole tree harvesting and sawlog harvest at 11 forest stands located throughout the United States. They reported that removals by whole tree harvesting were 98 to 650 lb/ac N, 9 to 86 lb/ac P, 31 to 291 lb/ac K and 99 to 972 lb/ac Ca. Our results were comparable for past studies. Although a respectable amount of nutrient was removed by fuel reduction thinning, this was only 5 to 10 percent of total site nutrient budgets found by Mann et al. (1988). Hacker (2005) also reported that removals of 90 percent of the above ground biomass caused reductions in only 6 percent or less of the total site nutrient capital. Therefore, thinning trees or biomass harvesting would remove only part of this above ground biomass and the nutrient depletion would be minimal except on nutrient poor sites with little organic matter in the mineral soils.

In tree components (i.e. stem and bark, branches, and foliage), nutrient concentrations of foliage were usually higher than those of stem and branches. However, N, P, and K at the site were removed with similar ratios in each tree component because dry mass of stem and branches was larger than foliage. 80 percent of total Ca removal was contributed by the removal of stem and branches.

Conclusion

ThinTool is an analytical tool designed and developed for use by forest managers, planner, and project contractors, in order to evaluate the cost of mechanical fuel reduction thinning including biomass removal, predict net energy output, and assess nutrient impacts from thinning treatments in northern California and southern Oregon. ThinTool can be used for ground-based thinning systems over a wide range of stand and site conditions, silvicultural prescriptions, operational requirements, and road standards and distances. Harvesting cost, net energy output, and site nutrient removal was directly linked to each other and sensitively responded to any change in thinning prescriptions (e.g. thinning intensity and species selection) and operations requirements (e.g. biomass recovery methods, machine size and skidding/yarding distance).

In this study, twelve different fuel reduction thinning studies that were done in the US west were comprehensively reviewed to identify key independent variables affecting the machine productivity. The amount of volume removed, tree size, percent slope, and skidding distances were identified as independent key variables affecting machine productivity in ground-based harvesting system. Representative machine productivity for sawlog removal increased as volume per acre of removal increased. Tree size and slope were found as key variables affecting feller-buncher productivity, while key variables for a skidder were skidding distance and slope. Feller-buncher productivity increased with increase tree size for sawlog production and the skidder productivity was reduced with increased skidding distances.

In model validation, the difference between ThinTool-simulated costs and the actual observed costs were 5 percent for sawlog production and 11 percent for biomass production. The total recoverable energy input and output were 215 and 3,245 MMBTUs, respectively. The net energy ratio between the recoverable energy output and the fossil energy input was 15.1. In site nutrient removal estimation from fuel reduction thinning treatment, the greatest nutrient removal was found in Ca and total removed biomass was only 5 to 10 percent of total site nutrient budgets.

Further research needs to focus on improving the prediction accuracy of the model by complementing the results from future fuel reduction thinning projects. When the model is complete we expect that it will be a useful tool to help forest managers and planners conduct fuel reduction treatments in a cost- and energy-effective while minimizing nutrient impacts.

References

Adams, T.C. 1983. Operational costs of harvesting logging residues for use as energy. Final report to U.S. Dept. of Energy, Bonneville Power Administration, per Interagency Agreement De-AI51- 81R000861. 64 pp.

Bolding, M.C., L.D. Kellogg, and C.T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. Forest Products Journal 59(3):35-46.

Fight R.D., Hartsough B.R. and Noordijk P. 2006. Users Guide for FRCS: Fuel Reduction Cost Simulator Software. U.S. Department of Agriculture, Forest Service. General Technical Report PNW-GTR-668.

Grigal, D.F., and E.D. Vance. 2000. Influence of soil organic matter on forest productivity. N.Z. J. For. Sci. 30:169 –205.

Hacker, J.J. 2005. Effects of Logging Residue Removal on Forest Sites: A Literature Review. West Central Wisconsin Regional Planning Commission. 29 p.

Hartsough, B.R., X. Zhang, and R.D. Fight. 2001. Harvesting cost model for small trees in natural stands in the Interior Northwest. Forest Products Journal. 51(4): 54-61.

Ince, P.J. 1979. How to estimate recoverable heating energy in wood or bark fuels. USDA Forest Serv., Forest Prod. Lab., Madison, Wisconsin. 10 pp.

Jenkins, J.C., D.C. Chojnacky, L.S. Heath, and R.A. Birdsey. 2003. National-scale biomass estimators for United States tree species. Forest Science 49(1):12-35.

Johnson, L.R. 1988. Final Report: Summary of production and time studies of mechanized harvesting equipment in the intermountain west. Forest Products Department, Univ. of Idaho, Moscow, Idaho. 129pp.

Lowell, E.C., D.R. Becker, D. Larson, R. Rummer, and L. Wadleigh. 2008. An integrated approach to evaluating the economic costs of wildfire hazard reduction through wood utilization opportunities in the southwestern U.S. Forest Science 54(3):273-283.

Mann, L.K., D.W. Johnson, D.C. West, D.W. Cole, J.W. Hornbeck, C.W. Martin, H. Riekirk, C. Smith, W.T. Swank, L.M. Tritton, and D.H. Van Lear. 1988. Effects of whole-tree and stem-only clearcutting on postharvest hydrologic losses, nutrient capital and regrowth. For. Sci. 34: 412-428.

Pan, F., H-S Han, L.R. Johnson, and W.J. Elliot. 2008a. Net energy output from harvesting small-diameter trees using a mechanized system. Forest Products Journal 58 (1/2) 25-30.

Pan, F., H-S Han, L.R. Johnson, and W.J. Elliot. 2008b. Production and cost of harvesting and transporting small-diameter trees for energy with a whole-tree system. Forest Products Journal 58 (5) 47-53.

Pearson, J.A., D.H. Knight and T.J. Fahey. 1987. Biomass and nutrient accumulation during stand development in Wyoming lodgepole pine forests. Ecology 68:1966-1973.

Ranger J, R. Marques, M. Colin-Belgrand, N. Flammang, and D. Gelhaye. 1995. The dynamics of biomass and nutrient accumulation in a Douglas-fir (*Pseudotsuga menziesii* Franco) stand studied using a chronosequence approach. Forest Ecology and Management 72: 167-183.

SAS Institute Inc. (SAS). 2003. SAS/STAT user's guide, Version 9.0. SAS, Cary, NC.

USDA Forest Service 2003. Large fire cost reduction action plan. Washington D.C., USDA Forest Service. 24 p.

Vitorelo, B.D. 2011. Cost and productivity of two mechanical fire hazard reduction methods: mastication and thinning. MS thesis. Humboldt State Univ., Arcata, CA. 77 pp.

Zhou, X. and M.A. Hemstrom. 2010. Timber volume and aboveground live tree biomass estimations for landscape analyses in the Pacific Northwest. Gen. Tech. Rep. PNW-GTR-819. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 31 p.

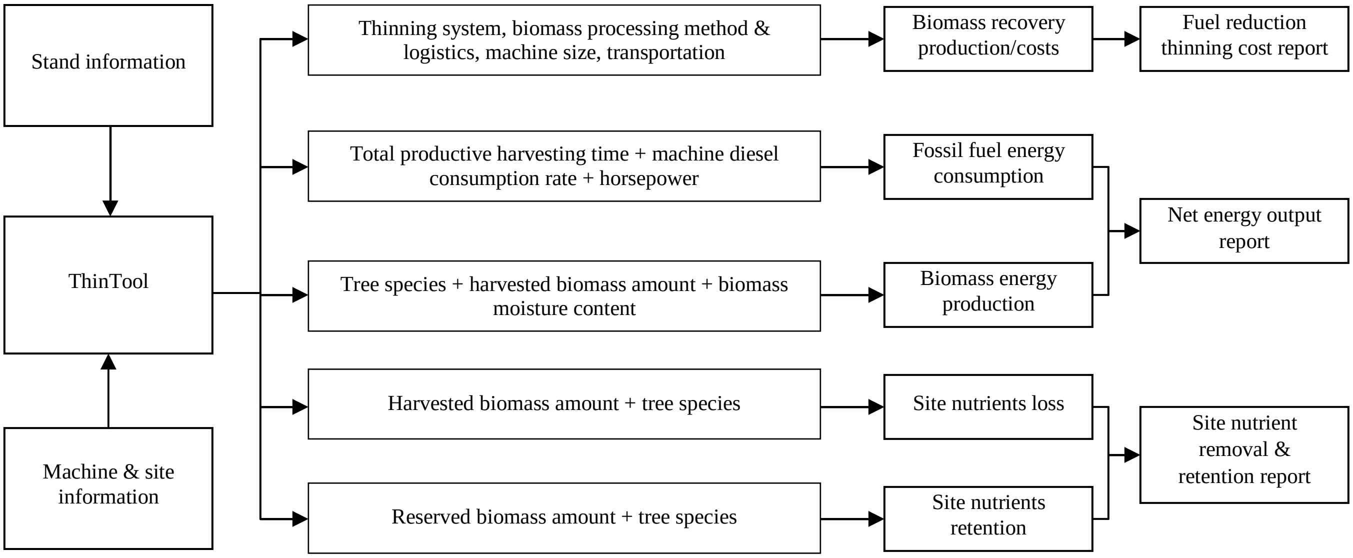


Figure 1: Fuel reduction thinning cost, net energy contribution, and site nutrient removals calculation model diagram.

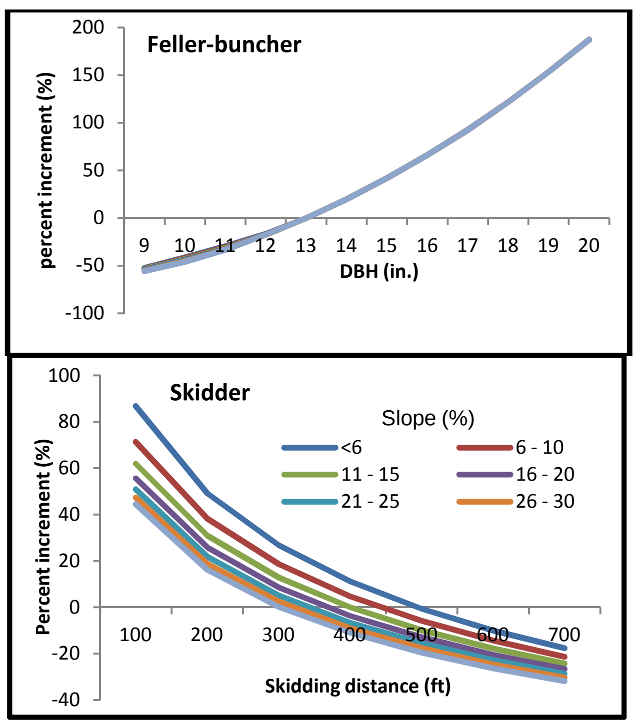


Figure 2. Adjustment factors for a feller-buncher and a skidder developed to adjust representative machine productivity in sawlog production

Table 1. Representative machine productivity (ft^3/PMH) of sawlog removal for each operation in ground-based system (Average skidding distance: 400 ft.).

	Sawlog Removal (MBF/ac)				
	4	7	10	DF[b]	p-value[c]
	-------------------- ft^3/PMH (SE[a]) -------------------				
Feller-buncher	1,323 (135)	1,556 (149)	1,696 (154)	38	0.0154
Skidder	906 (101)	1,087 (120)	1,181 (151)	35	0.7845
Processor	1,417 (147)	1,508 (154)	1,590 (149)	37	0.5394
Loader	1,792 (121)	1,854 (124)	1,920 (129)	36	0.5649

[a] SE = standard error
[b] DF = degrees of freedom
[c] p-value is significant at 0.05.

Table 2. Representative machine productivity (GT/PMH) of biomass removal for each operation in ground-based system (Average skidding distance: 400 ft.).

	Sawlog Removal (MBF/ac)				
	4	7	10	DF[b]	p-value[c]
	-------------------- GT/PMH (SE[a]) -------------------				
Feller-buncher	27 (3.51)	27 (4.01)	28 (4.29)	29	0.9349
Skidder	24 (3.05)	25 (3.58)	26 (4.15)	31	0.3445

[a] SE = standard error
[b] DF = degrees of freedom
[c] p-value is significant at 0.05.

Table 3. Sawlog harvesting cost (stump-to-truck) comparison between actual and simulated study in ground-based harvesting system

	Actual study	Simulated study
	---------------------------- $/$ft^3$	---------------------------
Feller-buncher	0.09	0.08
Skidder	0.17	0.16
Processor	0.11	0.09
Loader	0.05	0.10
Total	0.42	0.44

Table 4. Biomass harvesting cost (stump-to-truck) comparison between actual and simulated study in ground-based harvesting system

	Actual study	Simulated study
	---------------------------- $/BDT	---------------------------
Feller-buncher	20.72	14.16
Skidder	15.37	19.65
Loader	3.35	3.99
Grinder	12.97	9.04
Total	52.41	46.84

Table 5. Diesel consumption in a fuel reduction thinning using a ground-based system

	Feller-buncher	Skidder	Loader	Grinder	Chip van[a]	Total
Direct diesel input[b] (gallons)	66.3	88.8	72.7	361.2	955.2	1544.2
Heating value[c] (MMBTUs[d])	9.2	12.4	10.1	50.3	133.0	215.0
Average fuel consumption (gal/hr)	5.3	5.6	6.0	29.7	9.9	56.5
Percent total	4.3	5.7	4.7	23.4	61.9	100.0

[a]One-way travel distance was 55 miles.
[b]The amounts of fuel consumed for fuel reduction thinning were estimated using ThinTool.
[c]Based on 139,200 BTUs per gallon of diesel
[d]MMBTUs: Million British thermal unit

Table 6. Site nutrient removal estimated by ThinTool

	N	P	K	Ca	Mg
	--------------------------------		(lb/ac)[a]	--------------------------------	
Site nutrient removal	129.9	17.4	91.1	207.8	34.2

[a]The amounts of nutrient removal were estimated using ThinTool.

Analysis of harvesting logistics on woody biomass supply chains for community based bioenergy projects in West Virginia.

Damon S. Hartley[1] and Jingxin Wang[2]

Abstract

Woody biomass is being examined as the potential main feedstock for a wide array of bioenergy projects due to the fact that it can be used as either a combustion fuel or as a feedstock for the development of liquid fuels. However, the development of these bioenergy projects will be incumbent on the ability to source feedstocks at sufficient quantities and competitive prices. While the quantity of woody biomass that is potentially available has been shown to be sufficient to warrant the discussion of the development of bioenergy projects, investment in further development of bioenergy projects will require that assessments of the resource be accomplished at a more localized scale. Harvesting and transportation account for a majority of the delivered cost of woody biomass and are both affected by spatial factors such as terrain and spatial distribution. In this study, the harvest of biomass is modeled using spatial data in combination with logging system production data to determine the cost of biomass at the landing. Incorporating the results into a mixed integer linear programming model, the delivered cost of woody biomass is estimated for different usage scenarios. The results of this work will be useful to economic development agencies and government officials that are responsible for planning and implementing bioenergy projects.

Introduction

West Virginia as a state could benefit economically from the increased use of woody biomass as an energy feedstock. As a state, West Virginia is the second most forested in the United States, with 78% of the total area of the state being forest and 98% of the forest classified as timberland (FIA, 2011). Along with the abundant forest resource, it is estimated that the state produces approximately 2.41 million dry metric tons of wood residue annually (Wang et al, 2006). Traditionally, West Virginia has made use of the forests resource in traditional forest product industries, which contributed approximately four billion dollars annually to the state's economy (Childs, 2005). Following the national economic downturn and resulting reduction in the housing market, the industry has decreased production by about 40%. As a result the number of people employed by logging and wood manufacturing has fallen by 46% and 39% respectively since the year 2000, with the majority of job losses coming since 2007. In that period, logging has lost jobs at a rate of 11% per year and wood products manufacturing has lost jobs at a rate of 12.6% per year. In fact, the entire state has been effected by the economic downturn evident by the current unemployment rate of 8.1% and that nearly one-half of the counties in the state are classified as either economically distressed or at-risk (US Census Bureau, 2011; Appalachian Regional Commission, 2011).

[1] Graduate Research Assistant
[2] Professor West Virginia University, Morgantown, WV 26506

Traditionally, woody biomass has been considered a low value product, and consequently little emphasis has been placed on the efficient harvest, extraction and transport of this potentially valuable material. As energy markets develop, value will be added to these products and lead to increased harvest and collection (Becker et al., 2009). Even with the increases in market value associated with increased demand, harvesting and collection cost may be a limiting factor in the true availability of woody biomass feedstock. While collection and primary transport of logging residues can be completed using current timber harvesting systems, their efficiency is dependent on machine payloads; the terrain in which they are working; and the spatial distribution of the residue. Each one of these factors will affect the cost of the feedstock. In addition, transportation of woody biomass is also a challenge due to the material's low bulk density, making it difficult to maximize allowable load limits (Spinelli et al, 2007).

Methods

Study Area

Located in north central West Virginia, Monongalia county is nearly 74%, or 53532.8 hectare (ha) (132,226 acre (ac)), forested. The mean diameter for merchantable timber in this county is 26.31 cm (10.36 inches). FIA(2011) estimates that there are approximately 8.2 million dry tons of biomass in the area. If the merchantable portion of the stem is removed, approximately 2 million dry tons of biomass are available for harvest.

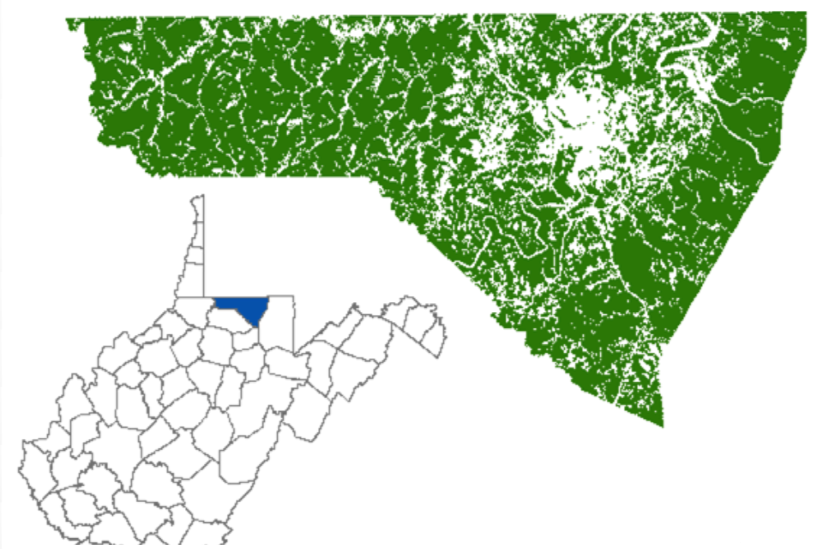


Figure 1. Map of Study Area

Harvesting system

The prevalent harvesting system utilized in the region is the chainsaw/cable skidder. It is assumed that all harvesting will be completed utilizing this type of system in a whole tree skidding, integrated harvesting scenario. Skidding the whole tree has been shown as an effective method for the collection of biomass, as the cost of primary transport is distributed over both the valuable saw log portion and the less valuable biomass portion (Grushecky et al, 2007). In addition to the chainsaw and cable skidder, the integrated harvesting system will also be equipped with a chipper at the landing to process the limbs and tops into a more energy dense form such as chips. A summary of the equipment and associated cost are given in Table 1.

Table 1. Cost and Utilization Rate of Biomass harvesting equipment

	Cable Skidder	**Chipper**
Hourly Cost	$81.34/SMH	$185.62/SMH
Utilization Rate	65%	37%

Extraction Route Generation

The delivered cost of forest derived woody biomass is dependent in large part on the costs related to the extraction of the resource. The cost of extraction is highly correlated to the topography in which the harvesting operations are taking place (Greulich et al. 1999). Using 9 meter (m) resolution digital elevation models, obtained from the Natural Resource and Analysis Center, and land cover data from National Land Cover Database (Fry et al.,2006), topographical information was gathered for all the forested areas in the study site.

Due to the lack of merchantable timber to justify commercial logging, all non-forested areas and forested areas smaller than 4.04686 ha (10 ac) were removed from the study area. Additionally, large areas of contiguous forest area were broken in to 39.7 ha (98 ac) harvesting units, to represent a typical harvest area for the region. Extraction routes for each harvesting site were simulated for each harvesting area using methods similar to those employed by Stückelberger et al. (2007) and Anderson and Nelson (2004). For each forested area an undirected, weighted graph was developed. The centers of each forested area grid cell were used as the nodes for the graph. Additionally, elevation was stored as an attribute for each point. Each node was connected to the neighboring 16 nodes (Figure 1) and slope distance was used as the weight parameter for each link (Eq 1). In an attempt to reduce the number of links that would need to be visited during the search process and to ensure that the average gradient of the extraction route would be less than 22% slope, links would only be added to the graph if the slope was less than or equal to 22%. In addition to the initial weights, for the links added to the graph, a slope penalty was implemented to ensure that there was a preference for flatter terrain.

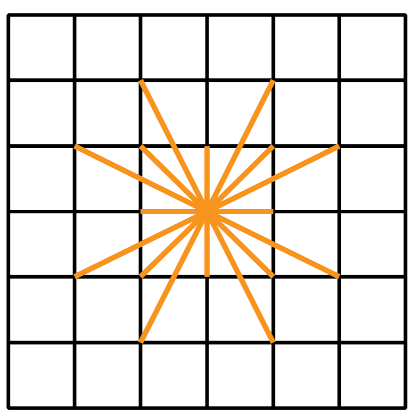


Figure 2. Diagram of Linking Pattern connecting 16 nodes

$$SD = \sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2} \qquad (1)$$

Upon completion of the graph of all cell nodes, supply points were designated and evenly distributed throughout the graph to serve as destination points for the extraction routes. The supply points were inserted into the graph on a 27m by 27m spacing to ensure that the entirety of the stand could be reached within economical line pull distances (Erikson et al., 1991). Landing locations were randomly selected from a point along the edge of the forested area, to serve as a starting point for path creation.

Extraction paths were determined from the landing point to each supply point, using a modified version of Dijkstra's algorithm implemented in Python 2.6. The original source code was written by Eppstein (2002), and modified to produce more realistic paths. The most notable modification was the addition of a direction of travel penalty, which penalized deviations of more than 45 degrees from the current direction of travel. Maximum payload for each path was determined using the method described by Phillips (1983) using Equation 2, where θ is the slope angle.

$$Payload = \frac{0.28cos\theta - sin\theta}{0.285cos\theta + sin\theta} \times Skidder\ Wt \qquad (2)$$

Results and Discussion

Extraction Path Generation

Extraction paths were calculated for 98 forested stands in Monongalia County. The stands ranged in size from 4.05ha to 37.25ha (10 to 93 ac) with a mean of 19.86 ha (49.05 ac). The distribution of stand areas can be found in Figure 3. The average skidding distance for all areas was calculated to be 233.9 m (767 ft.) with a range of 105.29 m to 531.11 m (345.44 ft. to 1742.49 ft.). Figure 4 provides an example of the extraction path that was created during the analysis. It can be noticed that some of the generated paths cross, while this would not be ideal in a real world scenario, for analysis purposes it is assumed that each path is independent and is determined by the least cost corridor for each supply point.

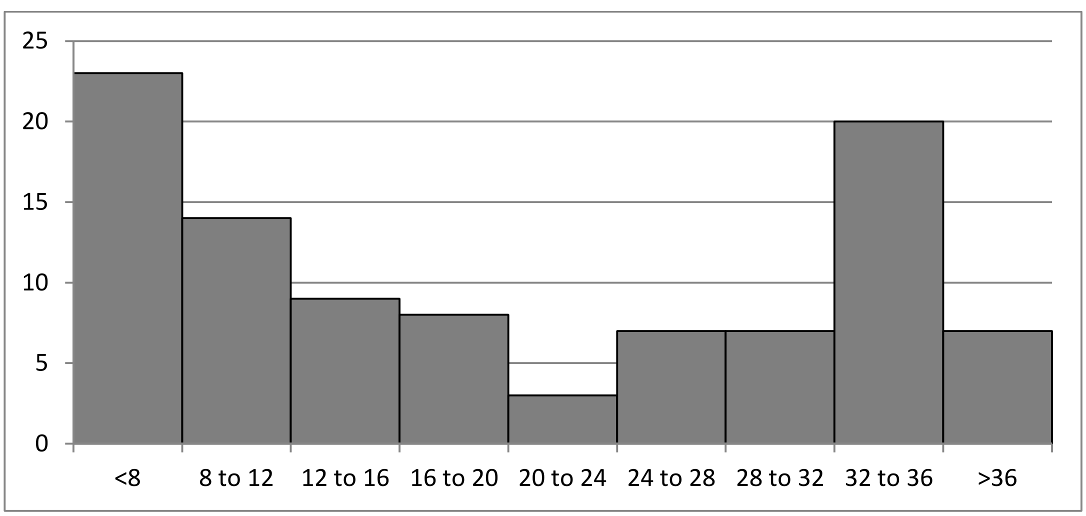


Figure 3. Area Distribution of Sample Harvest Areas

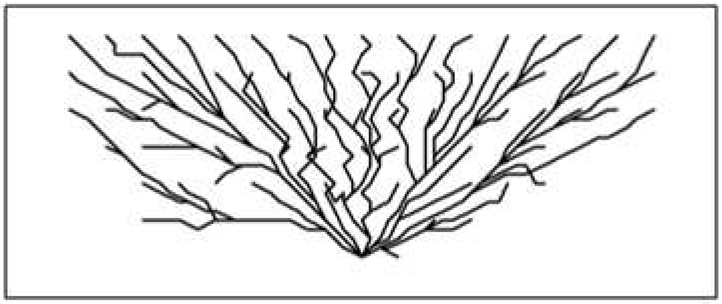


Figure 4. Example of Generated Extraction Path

Skidding Payload

Skidder payload is adversely affected by positive slopes (Figure 5). The design value of the skidder weight used in this analysis was 10335.75 kg (22 780 lbs). Additionally, the assumption was made that the maximum safe payload on flat ground and negative slopes was 9981 kg (22 000 lbs). For each harvest area, the maximum payload was limited to the minimum payload at any point between the supply point and the landing. This restriction resulted in sites having average maximum payloads ranging from 1228.2 kg to 9662.3 kg (2707 lbs to 21 295 lbs), with a weighted average of 2755.3 kg (6072 lbs).

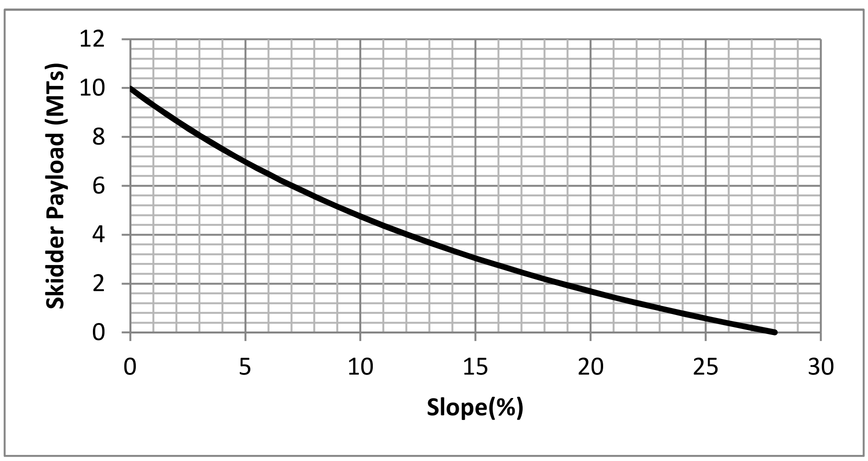


Figure 5. Effect of slope on skidder payload

Skidding Cost

The skidding cost was calculated based on skidder speed and maximum payload delivered to the landing. The average skidding cost of each site varied widely from $1.50 to $16.04 per dry MT. The large differences were due primarily to the relation of the landing to the primary direction of slope. More specifically, when landings were at the bottom of the slope larger payloads were possible. Moreover, if skidding was down slope on relatively gentle terrain, the cost was dramatically lower due to the combination of near maximum payloads and short skidding distances via more direct routes. The weighted average skidding cost for all sites was found to be $7.46 per dry MT. This value is considerably lower than the cost reported by WU (2010) for the extraction of residues as a secondary operation. In that study it was reported that the average cost attributable to skidding with a cable skidder was approximately $25 dollars per ton.

Cost of biomass at the landing
While the skidding cost constitutes a large portion of the cost of energy wood at the roadside, the final cost is determined by considering all the process involved until secondary transport. This means that if it is assumed that the chipping operation is being supplied by two skidders producing 5.63 dry MT per hour, a dedicated loader producing 9.36 dry MT per hour and chipper that is capable of producing 15 dry MT per hour, then the cost at road side will be approximately $26.56 per dry MT. The system is limited by loader productivity, assuming that the skidders do not reduce productivity to match the loader. This price is approximately 36% lower than the price found by Wu (2010) of $41.25 per dry MT at the landing.

Conclusions

Due to the relatively low value of woody biomass, especially forest residues, economical extraction require that the operations are both extremely efficient and productive. Currently, the majority of systems that are being examined are the traditional harvesting systems for a region. These systems have been designed and very successful in completing their intended purpose, the extraction of timber However for many logging companies, their costs and capabilities are not compatible with the smaller, less valuable material. It is because of the paradigm shift - bioenergy, those alternatives in both machinery and work method must be examined if fuels are to be made from these resources. Through the use of computer simulation it is possible to examine alternatives and, in certain cases, provide more localized resource estimates. This method provides a means in which to compare varying harvest tactics, extraction systems, and logging methods to determine the best fit option for a specific area or region. Previous work on the cost of biomass for this geographic area has focused on the extraction of residues as an a posteriori process. This study has shown that the concurrent removal of biomass for energy can have a large impact on the price at the landing, in this case a price reduction of more than one-third is achievable.

The removal of forest biomass in a whole tree logging system will have some operational concerns that will require further examination. It would be expected that the additional equipment required and increased material length and volume would require an increased landing size to accommodate these requirements. The addition of equipment would also increase the number of places and types of machine interactions. Both of these factors have the potential to impact the economic effectiveness of these operations. Also, with new work methods the optimal range of working conditions will need to be identified in order to deploy the developed systems where they can be most effective. For example, in this study there were several extraction paths that were at a cost level over $16/dry MT. It would be important to be able to identify these areas and designate them as inaccessible for the estimation of resources in a region. Further development of both the models and harvesting methods will provide tools needed to not only researches, but also resource managers, government planners, and energy developers to continue the development of projects that will advance the use of woody biomass as a renewable feedstock for energy and bio-products.

References

Anderson, A.E. and J. Nelson. 2004. Projecting vector based road networks with a shortest path algorithm. Canadian Journal of Forest Research 34:1444-1457.

Appalachian Regional Commission. 2011. County Economic Status and Number of Distressed Areas in West Virginia, Fiscal Year 2012. The Appalachian Region. Washington. Available at http://www.arc.gov/images/appregion/economic_statusFY2012/CountyEconomicStatusandDistressAreasFY2012WestVirginia.pdf. Accessed 8/05/2012.

Becker, D.R.,D. Larson and E.C. Lowell. 2009. Financial considerations of policy options to enhance biomass utilization for reducing wildfire hazards.Forest Policy and Economics.11(8):628-635.

Childs, R.A. 2005. West Virginia's forests: growing West Virginia's future. Bureau of Business and Economic Research, College of Business and Economics, West Virginia University. 14 p.

Erickson, M. D., C.C. Hassler and C.B. LeDoux. 1991. Productivity and Cost Estimators for Conventional Ground-based Skidding on Steep Terrain Using Preplanned Skid Roads.Proceedings: COFE 1991 Annual Meeting, August 22-25,Nanaimo, British Columbia, Canada. pp. 92-96.

Eppstein,D.2002.Dijkstra's algorithm for shortest paths (Python recipe). Available at http://code.activestate.com/recipes/119466-dijkstras-algorithm-for-shortest-paths/. Accessed 7/5/2012

FIA.2011.Forest Inventory Data Online(FIDO). Available at http://apps.fs.fed.us/fido/. Accessed 8/6/2012

Fry, J., Xian, G., Jin, S., Dewitz, J., Homer, C., Yang, L., Barnes, C., Herold, N., and Wickham, J., 2011. Completion of the 2006 National Land Cover Database for the Conterminous United States, *PE&RS*, Vol. 77(9):858-864.

Greulich, F.R., D.P. Hanley, J.F. McNeel and D. Baumgartner. 1999. A Primer for Timber Harvesting. EB 1316. WSU Cooperative Extension, Washington State University, Pullman, Washington. 40p.

Grushecky, S., J. Wang, and D. McGill. 2007. Influence of site characteristics and costs of trucking and extraction on log residue utilization in southern West Virginia. Forest Products Journal. 57(7/8): 63-67

Phillips, R.A. 1983. Skidder Load Capacity and Fuel Consumption HP-41C Program. Res. Pap. NE-537. USDA Forest Service, Northeastern Forest Experiment Station. Broomall, PA. 7p.

Spinelli, R., C. Nati, and N. Magagnotti. 2007. Recovering logging residue: experiences from the Italian Eastern Alps. *Croatian Journal of Forest Engineering*. 28: 1-9.

Stückelberger, J., H.R. Hinimann and W. Chung. 2007. Improved road network design models with the consideration of various link patterns and road design elements. Canadian Journal of Forest Research. 37:2281-2298

US Census Bureau. 2011. Local Employment Dynamics. Washington, DC: United States Census Bureau. Available at http://lehd.did.census.gov/led/datatools/qwiapp.html. Accessed 8/06/2012

Wang, J., S. Grushecky, and J .McNeel,. 2006. *Biomass Resources, Uses, and Opportunities in West Virginia*. West Virginia University, Biomaterials Center, Morgantown, WV.

Wu, J. 2010. Development of Economic Analysis Models for Woody Biomass to Biofuels in Central Appalachia. Dissertation. Davis College of Agriculture, Natural Resources and Design, West Virginia University, Morgantown, WV. 206p.

Cycle Time Analysis of Harvesting Equipment from an Early-Commercial-Thinning Treatment in Maine

Patrick Hiesl[1], Jeffrey G. Benjamin[2]

Abstract

In the summer of 2011 researchers at the University of Maine conducted an early commercial thinning (ECT) treatment in a stand initiated from a clear-cut approximately 40 years ago. The study included four pieces of harvesting equipment (two harvesters and two feller-bunchers) and two different trail spacings (15.2 m (50 ft) and 24.4 m (80 ft)). The two harvesters (Ponsse Fox and John Deere 1170E) and one feller-buncher (CAT 501) were new machines donated by local equipment dealers for use in the study. The second feller-buncher (John Deere 753J) was a mid-sized machine commonly used in Maine. The objectives of the study included determination of the effect of stem size and trail spacing on cycle times of the various machines. Results of this study show that there is a significant ($p<0.05$) difference in cycle time per species and DBH for the harvesters. All species included in the analysis of the two trail spacings indicated that there are significant ($p<0.05$) differences in cycle time with an average difference of approximately 14 seconds per tree. The difference within individual tree species for the two trail spacings is up to 25 seconds per tree. Results for the feller-buncher show that there is a significant ($p<0.05$) difference in cycle time between stems harvested from trails and from the surrounding stand, but there is no significant ($p<0.05$) difference in the cycle time between the 15.2 m (50 ft) and 24.4 m (80 ft) trail spacing.

Keywords: early commercial thinning, cycle time, harvester, feller-buncher, stem size, trail spacing, Abies balsamea, piece volume

Introduction

According to FIA data (FIA 2004-2008) there are 0.6 million hectares (1.5 million acres) of 20 to 39 year-old spruce-fir forests in Maine and an additional 0.36 million hectares (0.9 million acres) in the 40 to 59 year-old class. Regenerating from clearcuts during the budworm era, many of these areas are dominated by dense spruce and fir saplings with diameters smaller than 15 cm (6 in.) in DBH with a small component of hardwoods. Pre-commercial thinning has been done in some of these stands; others, however, have grown beyond the stage at which brush-saw treatment is feasible. Such stands are overstocked and would benefit from thinning, but they are decades away from being operable with traditional harvesting systems. The Maine Forest Service (2008) estimates that thinning these overstocked stands could provide an additional 1.4 million green tons of wood annually.

[1] Graduate Research Assistant.University of Maine. patrick.hiesl@maine.edu
[2] Associate Professor of Forest Operations. University of Maine. jeffrey.g.benjamin@maine.edu

There is no consensus within the industry as to how these young stands should be treated. Given the presence of an active regional energy wood market, and because the dominant harvest method in Maine is still whole-tree, it is important to look into thinning treatments from a different perspective. Based on the cooperation of equipment dealers and manufacturers, landowners, and contractors, an early commercial thinning (ECT) study was carried out, funded by the Cooperative Forestry Research Unit (CFRU). Local equipment dealers and manufacturers are eager to test their versions of specialized equipment that is commercially available for both harvesting and transporting this material to the roadside. The conducted research allowed three sectors of the forest industry (landowners, contractors, and equipment dealers and manufacturers) to develop silviculturally effective, operational solutions for implementing early commercial thinning treatments.

This paper will look in detail into the cycle time of cutting individual trees with feller-bunchers and harvesters. To make informed decisions about what piece of equipment to use for cutting these young stands it is important to know the time it takes to cut and process these trees, especially with today's high machine rates. This analysis will compare the cycle time for cutting various tree species in small diameter classes between feller-bunchers and harvesters. It will also show the cycle time differences of the individual species. A "finesse" and a "production" operator were used for each type of machine to represent a large variety of operator proficiency and style.

Objectives

The objectives of this study are to determine the cycle time differences of harvesters and feller-bunchers in small diameter wood with respect to:

- species measured in terms of within and between species differences;
- piece volume measured in terms of species independent merchantable volume; and
- trail spacing

Methods

For this study, 22 plots, each 809 m^2 (0.2 acres) were established along harvest trails (15.2 m (50 ft) and 24.4 m (80 ft) spacing) in a pre-commercially thinned (PCT) stand. All plots were designed to be 809 m^2 (0.2 acres) in size regardless of trail spacing. The plot sizes were 15.2 m x 53.1 m (50 ft x 174.2 ft) and 24.4 m x 33.2 m (80 ft x 108.9 ft) with the area in trails estimated at 25% for the 15.2 m (50 ft) spacing and 16% for the 24.4 m (80 ft) spacing. Fourteen plots were laid out in the 24.4 m (80 ft) spacing pattern while eight were laid out in the 15.2 m (50 ft) spacing pattern. Each plot was inventoried using a 100% tally for DBH and species down to a 2.5 cm (1 in.) DBH class. The initial tree density was 672 trees per hectare (272 trees per acre) with a 3.9 m (12.7 ft) spacing and a basal area of 38 m^2/ha (167 $feet^2$/acre). The carried out prescription was to remove approximately 50% of the basal area. More details about the prescription and the stand origin can be found in Benjamin et al. (2012). Roughly half of the soil on site consisted of a very stony loam while the other half consisted of a very stony silt loam. Two harvesting methods (CTL and WT) were used to harvest two products (pulpwood and biomass, and biomass only). A time and motion study was carried out to collect cycle time data for each piece of equipment.

The research was conducted in the Summit Township about 40 km (25 miles) from the University of Maine campus on approximately 8 ha (20 acres) of pre-commercially thinned stands. The harvesting equipment and operators were provided at no cost from Nortrax & John Deere, Milton CAT, Chadwick BaRoss & Ponsse and one individual contractor. Table 1 shows the equipment selection for this study as well as the specifications of each piece of equipment.

Time and Motion Study

Within each plot all trees have been painted with four different colors in 5 cm (2 in.) DBH classes. A series of colors has been used to paint the first set of DBH classes. After reaching the last color for a DBH class the first color was used again to paint the next DBH class and so on. This assured that each color was used for a small diameter and large diameter class. Painting trees in DBH classes has also been carried out by Glade (1999) and Eggers et al. (2010). A PALM Tungsten E2 in combination with the time study software UMT plus (LAUBRASS Inc.) was used to collect cycle time data for each machine. Using a two-way radio with a headset ensured communication between the operator and the researcher to provide the latter with the tree species and color code. The information was immediately entered into the PDA and the time measurement started. A definition of the cycle for the feller-buncher and harvester can be found in Table 2.

Results

Cut-To-Length

Cycle times were collected for a total of 1042 trees for DBH classes between 2.5 cm (1 in.) and 48 cm (19 in.). Due to the small amount of data collected in DBH classes greater than 38 cm (15 in), only data for trees between 13 cm (5 in.) and 38 cm (15 in.) DBH was used for this analysis. Further, instances of multi-stem processing (MSP), cutting snags and chain throws were removed from the dataset which results in a total of 728 trees for the data analysis. Table 3 shows detailed information of species as well as collected and analyzed trees.

A series of Welch's Two Sample t-tests were conducted for four groups of species to investigate the differences between the cycle times of these groups to each other. Due to the small amount of red pine (Pinus resinosa) samples this species was combined with the samples of eastern white pine (Pinus strobus). The group HW (Hardwoods) consists of the red maple (Acer rubrum) and paper birch (Betula papyrifera) samples. All groups were formed regardless of trail spacing. The results of these tests can be found in Table 4. A significant difference ($p<0.05$) can be found between all groups for the cycle time except the comparison of red spruce (Picea rubens) and eastern white pine. This particular combination shows no significant difference in cycle time variation at the 95% significance level with a p-value of 0.099.

Figure 1 shows boxplots of DBH class and cycle time for the individual species groups. Balsam fir (Abies balsamea) and red spruce show no significant ($p>0.05$) difference in cycle time among the different DBH classes while white pine and hardwood do. Figure 2 shows a boxplot with the cycle times based on the piece volume in cubic meter. The trend that can be seen is that the cycle time increases with an increase in the piece volume. The drop in cycle time in the 0.8 m^3 (28 ft^3) and 1.2 m^3 (42 ft^3) category can be explained with the small sample size in those piece volumes.

Differences between two trail spacings
This study was set up with two different trail spacings, 15.2 m (50 ft) and 24.4 m (80 ft) to investigate if there are differences in cycle time between those two. The result of Welch's Two Sample t-test suggests that there is a significant difference ($p=1.29e-07$) between the cycle times of the two trail spacing, with an average cycle time increase of approximately 14 seconds for the 24.4 m (80 ft) spacing. The analysis of the cycle times of the individual species in those spacings shows that there are significant differences ($p<0.05$) in the cycle time for balsam fir, red spruce and white pine. For the hardwoods, however, there is no significant difference between the two trail spacings. The increase in cycle time ranges from approximately 8 seconds to 25 seconds. Table 5 shows the results of these t-tests. Figure 3 shows boxplots for the cycle time for the 15.2 m (50 ft) and 24.4 m (80 ft) trail spacing.

Whole-Tree
A total of 1043 trees were captured by the time and motion study for the whole-tree harvesting method in this study. The accumulation in a feller-buncher head will be referred to as a bunch in this paper. A total of 341 bunches were captured for the two feller-bunchers studied. The layout of the study was to separate trees harvested in a trail and trees harvested in a plot in the data collection process. Table 7 shows the information of total trees and bunches collected as well as the information about trees in trails and trees in plots. Due to snag removal or the cutting of regrowth of red maple the dataset was reduced to 844 trees or 254 bunches that were analyzed. The distribution of tree species harvested can also be seen in Table 6.
The results of a series of Welch's Two Sample t-test is that there is no significant ($p<0.05$) difference in the cycle time between the individual species. Due to the small sample size of red pine this species has been combined with the eastern white pine samples. The species group HW (hardwoods) consists of the species of red maple, paper birch, yellow birch (Betula alleghaniensis), gray birch (Betula populifolia) and quaking aspen (Populus tremuloides). Figure 4 shows boxplots of the cycle time for all species. Boxplots of the cycle time for each species based on the DBH class can be seen in Figure 5. The variation in cycle time seems to be about the same throughout the DBH classes with the exception of red spruce. Analyzing the cycle time based on the piece volume shows that the variability of the cycle time for each volume category is not significantly ($p<0.05$) different from another. The only exception is the comparison of the 0.1 m^3 (3.5 ft^3) category with the 0.5 m^3 (18 ft^3) category with a p-value of 0.023 based on Welch's two sample t-test. Figure 6 shows the boxplots with the cycle time for the piece volume categories.

The analysis of the accumulation of plot-trees and trail-trees within a bunch using Welch's Two Sample t-test shows that there is a significant (p=0.047) difference in cycle time between trees cut in trails and trees cut in the surrounding plot. The analysis shows that the accumulation of a bunch in the trail takes, on average, 23 seconds longer. Based on a t-test there is no significant difference in the cycle time (p=0.148) or stem count (p=0.099) between the 15.2 m (50 ft) and 24.4 m (80 ft) trail spacing. The results of the t-tests can be found in Table 7.

Discussion

The result that there is no difference in cycle time between eastern white pine and red spruce, when cutting with a harvester, might be due to the difference in sample size (n_{WP}=185; n_{RS}=66). The large sample size of balsam fir (n_{BF}=438) might also be a factor that needs to be considered when comparing to other groups with much lower sample sizes (e.g. n_{HW}=39). The results of the t-tests (Table 4) suggest that species is a relevant factor regarding cycle time outcome. Fitting linear regression models for each tree species with DBH further confirms the results of many studies (e.g. Adebayo 2007, Nakagawa et al. 2007, Bolding et al. 2009, Spinelli et al. 2010) that DBH is a significant factor ($p<0.05$) in predicting cycle time. However, the R^2 values of between 0.0005 and 0.34 suggest that the range of tree size for balsam fir is not large enough to observe a difference in cycle time as well as red spruce and the hardwoods. A trend in increased cycle time with increasing DBH can be seen with eastern white pine which is probably due to increased delimbing time. Table 8 shows the models developed and the associated R^2 values.

The difference in cycle time based on the trail spacing might be explained with the additional time it takes to position the harvester to cut trees at maximum distance. As can be seen in Table 5 the mean cycle time for hardwoods is up to three times higher than the mean cycle time for the other species, which might be explained by the extra time it takes to cut off large branches in the delimbing process.
The results of the harvester analysis show that the harvester is optimal for cutting 13 cm (5 in.) to 30 cm (12 in.) balsam fir and red spruce. The processing time stays about the same for the whole DBH range. When working with eastern white pine, trees from 13 cm (5 in.) to 23 cm (9 in.) take about the same processing time as balsam fir and red spruce. Beyond 23 cm (9 in.) the processing time increases immensely (see Figure 1). Hardwoods on the other side just take a long time to process. The long processing times for eastern white pine and hardwoods are most likely due to thick branches which affect the processing time, as reported by Glade (1999). The results from this study show the optimal range of DBH and species when cutting small diameter wood with a harvester. When looking at the piece volume of the individual trees, the cycle time variability stays about the same between the 0.1 m^3 (3.5 ft^3) and 0.5 m^3 (18 ft^3) volume class. Beyond that the data is limited but shows that the variability increases greatly. Using the harvester in stands with an average tree volume of less than 0.5 m^3 (18 ft^3) will result in the best cycle time performance for this type of machine. In regards to the trail spacing the results clearly show that smaller trail spacings increase the average

cycle time. This, however, also means that the area in trails will be increased. The loss of growth on these extra trails needs to be accounted for when deciding if the reduction in cycle time is worth more than the loss of tree growth over time.

The results of the feller-buncher analysis show that the cycle time for the individual species and DBH classes stays about the same with the exception of red spruce. Reason for this exception might be the small sample size (n_{RS}=50) divided into five DBH classes. Comparing the cycle times based on the piece volume shows no significant differences with one exception. A reason why there is no difference between the cycle times of the individual piece volumes might be the small sample size of piece volumes greater than 0.5 m^3 (18 ft^3) with mostly three samples per category.

Looking into the difference in cycle time between bunches of trees cut in trails and trees cut in plots shows that there is an increase in the cycle time for cutting trail trees. This increase is due to the higher stem count of each bunch cut in trails. Another reason might be that while cutting trails, bunches have to be placed off the trail to ensure that the feller-buncher can travel on the trail. This takes additional time compared to just lying down bunches in the trail.

The conclusion for the feller-buncher is that the cycle time is independent of species. The cycle time is also independent of the DBH within the individual species. Further, the cycle time variability is the same for the piece volumes up to 0.5 m^3 (18 ft^3). For the thinning of small diameter wood this means that the feller-buncher can cut a wide array of species and DBH without cycle time increase. Compared to the harvester this information is useful when operating in stands with larger white pine or a great hardwood amount. Based on the time it takes to cut certain trees, the cost can be calculated and weighed with the approximate amount of revenue from the cut wood. Since there is no difference in the cycle time based on the two trail spacings a wider spacing can be used to decrease the area in trail and to increase the area of future tree growth.

In general the feller-buncher is faster in cutting trees compared to the harvester, however, the additional time used for processing trees with a delimber is not included in this analysis and has to be accounted for when comparing these two machines to each other.

References

Adebayo, A.B., H.-S. Han, and L. Johnson. 2007. Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. Forest Products Journal 57(6): 59-69.

Benjamin, J.G., E. Meacham, R. Seymour, and J. Wilson. 2012. Early Commercial Thinning Harvest Systems: A Silvicultural and Operational Assessment. Project Update and Preliminary Results. Presentation at the Forest Reources Association – Industrial Forum in Bangor, ME. February 2, 2012.

Bolding, M.C., L.D. Kellogg, and C.T. Davis. 2009. Productivity and costs of an integrated mechanical forest fuel reduction operation in southwest Oregon. Forest Products Journal 59(3): 35-46.

Eggers, J., A. McEwan, and B. Conradie. 2010. Pinus saw timber tree optimization in South Africa: a comparison of mechanised tree optimisation (harvester/processor) versus current manual methods. Southern Forests 2010, 72(1): 23-30.
Glade, D. 1999. Single- and Double-Grip Harvesters – Productive Measurements in Final Cutting of Shelterwood. Journal of Forest Engineering, 63: 63-74.
Maine Forest Service. 2008. Maine Forest Service Assessment of Sustainable Biomass Availability. www.maine.gov/doc/mfs/pubs/pdf/biomass_memo_071708.pdf. Accessed 02/18/10.
Nakagawa, M., J. Hamatsu, T. Saitou, and H. Ishida. 2007. Effect of Tree Size on Productivity and Time Required for Work Elements in Selective Thinning by a Harvester. International Journal of Forest Engineering 18(2): 24-28.
Spinelli, R., B.R. Hartsough, and N. Magagnotti. 2010. Productivity Standards for Harvesters and Processors in Italy. Forest Products Journal 60(3): 226-235.

Table 1: Equipment selection for the early commercial thinning (ECT) study.

ECT Study - Equipment selection

Machine	Specifications				
	Width	**Weight**	**Reach**	**Clearance**	**Gross Power @ 2000 rpm**
John Deere 1070E	2.6 m (8.5 ft)	14.7 t (32,400 lbs)	10.7 m (35 ft)	0.56 m (22 in.)	136 kw (182 hp)
Ponsse Fox	2.7 m (9.0 ft)	17.7 t (39,000 lbs)	10.0 m (33 ft)	0.61 m (26 in.)	147 kw (197 hp)
CAT 501	2.6 m (8.5 ft)	15.9 t (35,000 lbs)	7.0 m (23 ft)	0.66 m (24 in.)	157 kw (157 hp)
John Deere 753J	3.2 m (10.5 ft)	23.6 t (52,000 lbs)	8.2 m (27 ft)	0.74 m (29 in.)	164 kw (220 hp)

Table 2: Cycle time definitions for feller-buncher and harvester.

Machine Type	Work Cycle Description
Feller-Buncher	Begins and ends at empty accumulators at the bunch and includes the time to harvest, accumulate, and place a bunch in a twitch.
Harvester	Begins and ends at saw cut and includes the time to fell, delimb, top, process, and select the next stem. If multi-stem processing occurs, the cycle will end after all stems have been processed and a new stem is selected with empty accumulators.

Table 3: Data collection and tree species information for the cut-to-length harvesting method.

Cut-To-Length Information

Data collection

Total trees	n = 1042
Trees between 13 cm (5 in.) and 38 cm (15 in.)	n = 747
Trees analyzed	n = 728

Tree species

Balsam Fir (Abies balsamea)	n = 438
Eastern White Pine (Pinus strobus)	n = 182
Red Spruce (Picea rubens)	n = 66
Red Maple (Acer rubrum)	n = 29
Paper Birch (Betula papyrifera)	n = 10
Red Pine (Pinus resinosa)	n = 3

Table 4: Welch's two sample t-test results for comparing cycle times between species groups.

Cut-To-Length differences between species

Welch Two Sample t-test

Difference between cycle times [sec]

Species	mean ssp. 1	mean ssp. 2	p-value	df	signif. level
BF - RS	35.31	43.49	0.0343700	77.159	.
BF - WP	35.31	51.20	5.144E-07	238.830	***
BF - HW	35.31	84.46	1.739E-05	38.917	***
RS - WP	43.49	51.20	0.0989100	150.838	
RS - HW	43.49	84.46	0.0003388	48.281	**
WP - HW	51.20	84.46	0.0025060	44.517	*

signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '

BF = balsam fir RS = red spruce
WP = white pine + red pine HW = red maple + paper birch

Table 5: Welch's Two Sample t-test's for the differences between 50 feet and 80 feet trail spacing in cycle time for the cut-to-length harvesting method.

Cut-To-Length differences between two trail spacing

Welch Two Sample t-test

Difference between 15.2 m (50 ft) and 24.4 m (80 ft) trail spacing

Difference in:	mean 15.2 m (50 ft)	mean 24.4 m (80 ft)	p-value	df	signif. level
cycle time	36.90	50.45	1.290E-07	591.129	***

Differences between tree species in 50 feet and 80 feet trail *spacing*

Difference in:	**mean 15.2 m (50 ft)**	**mean 24.4 m (80 ft)**	**p-value**	**df**	**signif. level**
BF - cycle time	32.29	40.61	3.418E-05	358.605	*******
RS - cycle time	34.57	59.11	0.007270	27.887	*****
WP - cycle time	43.54	62.67	0.001672	133.625	*
HW - cycle time	95.02	79.18	0.504100	19.311	

cycle time in seconds

signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '

Table 6: Information about collected data for the whole-tree harvesting method.

Whole-Tree Information

Data collection

Total trees	n = 1043
Total bunches	n = 341
Plot-trees	n = 751
Trail-trees	n = 292

Analyzed data

Trees analyzed	n = 845
Bunches analyzed	n = 254
Plot-trees	n = 674
Plot-bunches	n = 215
Trail-trees	n = 171
Trail-bunches	n = 39

Tree species

Balsam Fir (Abies balsamea)	n= 625
Eastern White Pine (Pinus strobus)	n = 122
Red Spruce (Pices rubens)	n = 50
Red Maple (Acer rubrum)	n = 23
Paper Birch (Betula papyrifera)	n = 18
Red Pine (Pinus resinosa)	n = 3
Gray Birch (Betula populifolia)	n = 1
Quaking Aspen (Populus tremuloides)	n = 1
Yellow Birch (Betula alleghaniensis)	n = 1

Table 7: Data analysis for plot-trees and trail-trees.

Whole-Tree data analysis for bunches

Welch's Two Sample t-test

Difference between plot-trees and trail-trees

Difference in:	mean plot-tree	mean trail-tree	p-value	df	signif. level
cycle time	65.30	88.30	0.04726	43.755	.
stem count	3.13	4.38	0.01672	43.455	.

Difference between trail spacing for plot-trees

Difference in:	mean 50 feet	mean 80 feet	p-value	df	signif. level
cycle time	60.03	68.17	0.1483	197.300	
stem count	2.87	3.28	0.09901	188.519	

cycle time in seconds

signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '

Table 8: Linear models for all tree species and the associated R^2-value.

Cut-To-Length linear models for all tree species

Linear models (DBH in inches)

Species	Model	R^2
Balsam Fir	Cycle Time = 33.20 + 0.35*DBH	0.00050
Red Spruce	Cycle Time = 34.41 + 1.26*DBH	0.06957
White Pine	Cycle Time = 22.88 + 9.74*DBH	0.34090
Hardwoods	Cycle Time = 10.05 + 7.54*DBH	0.15650

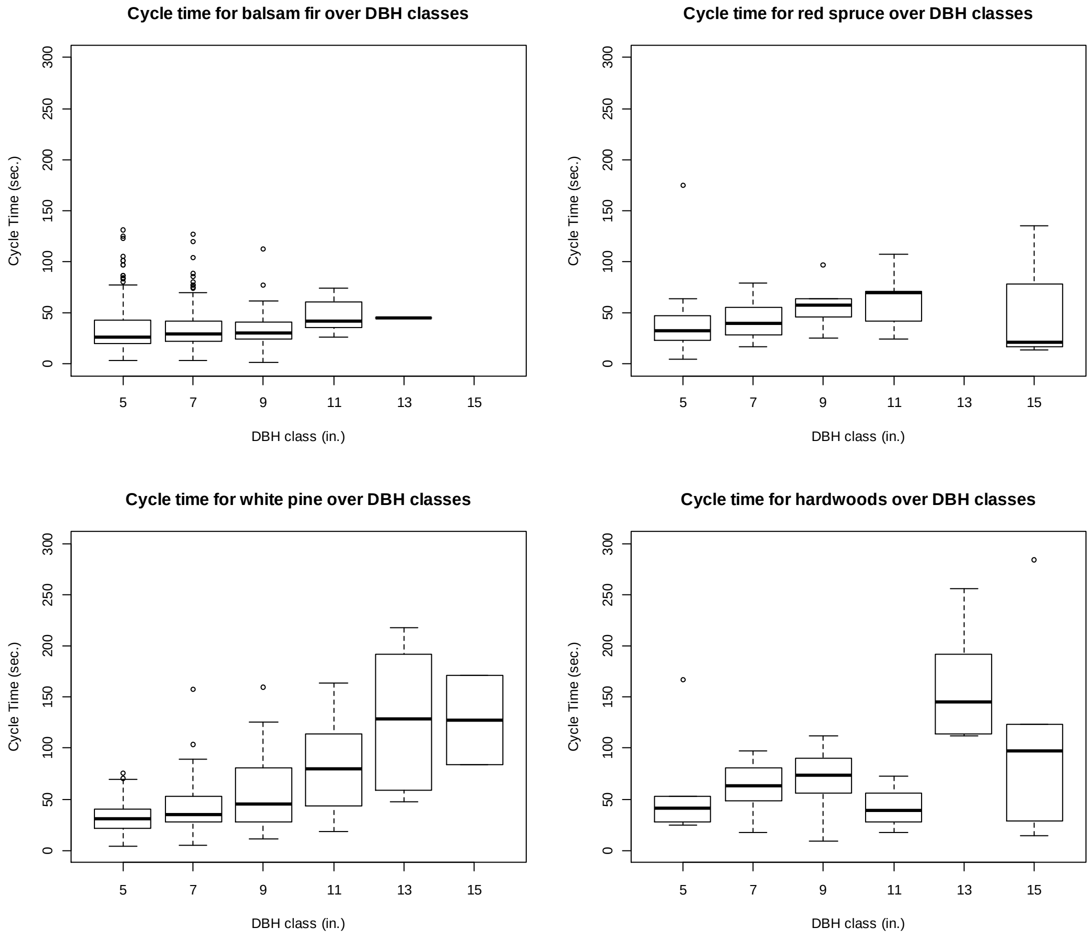


Figure 1: Boxplots with cycle times for various species and DBH classes for the cut-to-length harvesting method.

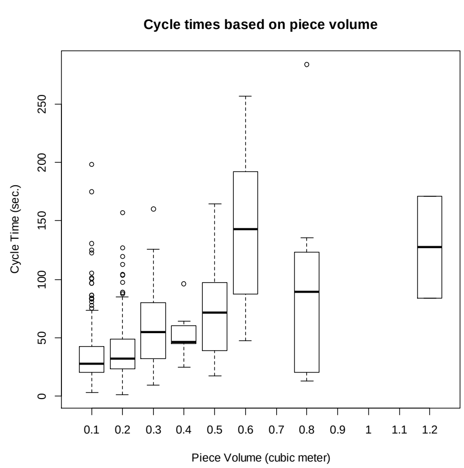


Figure 2: Cycle times based on the piece volume in cubic meter for the cut-to-length harvesting method.

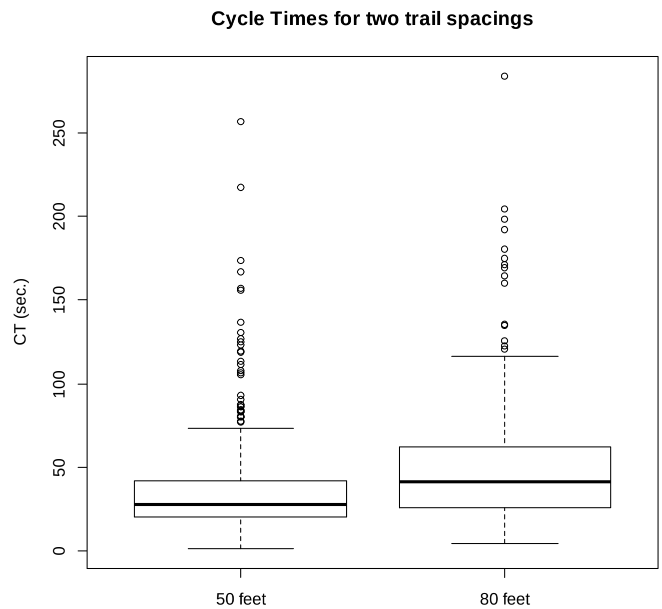


Figure 3: Boxplot with cycle times for harvesters operating in two different trail spacing.

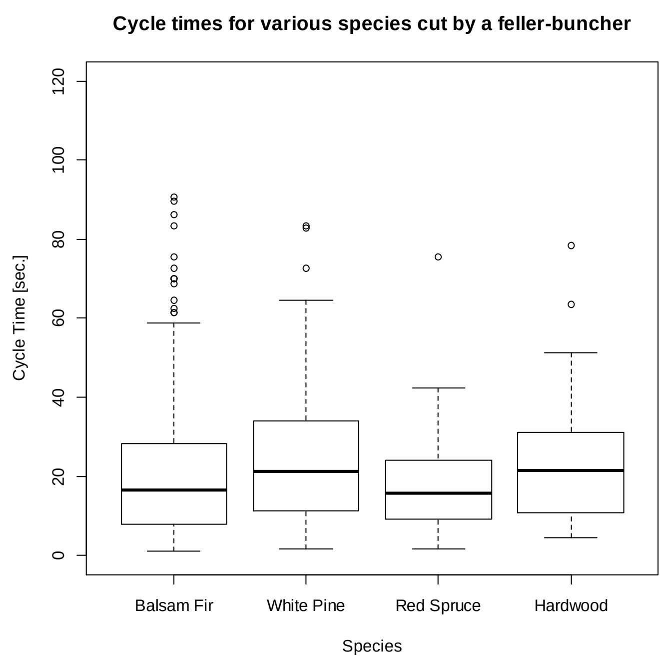


Figure 4: Boxplots with cycle times for individual species cut by a feller-buncher.

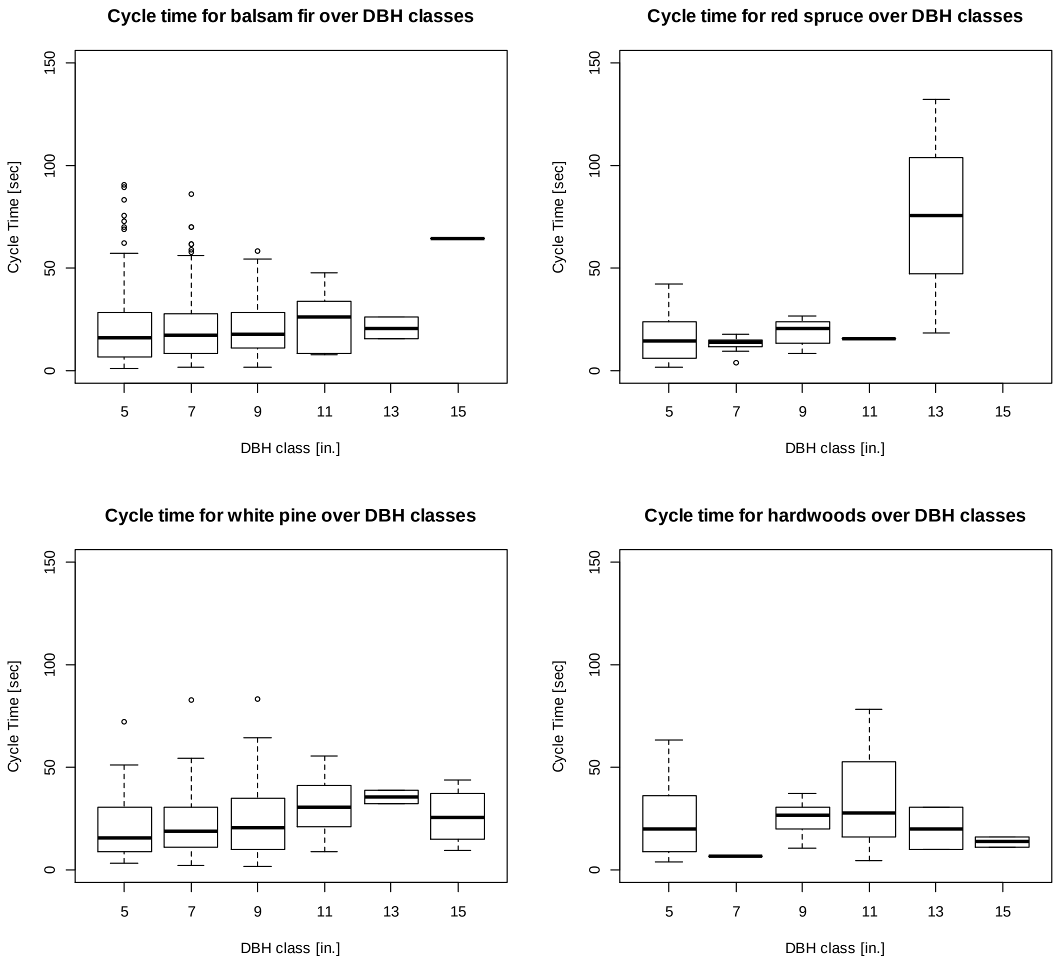


Figure 5: Boxplots of cycle time for individual species and DBH classes in the whole-tree harvesting method.

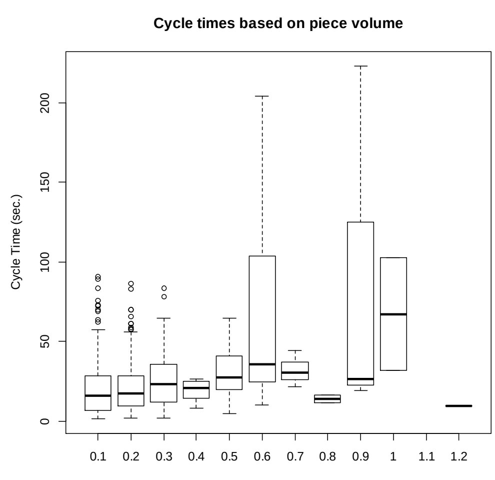


Figure 6: Boxplots with cycle times based on the piece volume of trees cut by a feller-buncher.

Microchiping Trials of Green versus Dry, Pine versus Hardwood: Measurement of Energy Efficiency and Productivity

Chris Hopkins[1] and Joseph Roise[2]

Introduction

Dry wood has higher net energy content than green wood and transporting water in wood is expensive, however current forest harvest procurement procedures pay by delivered weight thus rewarding the transport of moisture content and not the delivery of energy. A feedstock producer gets paid the same for a ton of dry wood as for a ton of green wood, but (air) dry wood has 75% more usable energy than green wood (per unit weight). North Carolina State University is developing efficient woody biomass logistics that take advantage of natural drying processes at the harvest site to increase net energy content per ton and decrease the delivered cost per unit of energy. In-field drying is not current practice in the Southeast of the United States, but implementing a dry wood delivery system would result in significant benefits to the burgeoning forest fuels and energy production market, including:

- lowering delivered energy costs by approximately 43% per unit wood
- increasing the supply of energy from forest resources by 36%
- motivating wood producers to deliver energy value instead of weight

One of the key steps to realize the benefits of in-field drying is to quantify the operation of chipping field dried wood. A key partner in this work is Peterson Corporation which has provided the use of a 4300 12 pocket drum chipper for the production of microchips from field dried wood in this study. This chipper is equipped with a water injection system that allows the chipping of dry material without the heat up and excessive blade wear of un-cooled chipping equipment. Microchips are small woodchips with the largest face dimension less than 3/8" in length (Steiner 2011).

Methods

To simulate in-field drying conditions, biomass was dried on log trailers in 2011 and 2012. Several treatments of biomass were tried in these trials: piece size, species group and coverings. Two treatments of piece size were studied; non merchantable top wood (less than 6" in diameter at butt end) and top wood attached to the first log of pulpwood. Two species groups were also studied, pines (dominated by loblolly pine (Pinus taeda) and mixed hardwood (sweetgum, red maple, oaks, hickories). Finally, trailers were covered by a secured paper tarp (Walki, 2010) or left exposed to precipitation. Trailers were allowed to dry for approximately 8 months in 2011 (February

[1] Outreach Associate. North Carolina State University
[2] Professor and Director of Graduate Programs, Department of Forestry and Environmental Resources .North Carolina State University

to September) and 7 months in 2012 (January to July). Trailers were weighed on a bi-weekly basis to follow their patterns of drying. No significant difference in weight change between covered and uncovered trailers were found.
Chipping was accomplished with a Peterson 4300 drum chipper with 12 pockets and water injection. Several parameters of chipping were measured: overall input/output efficiency of chipping by weight, time to chip a trailer, and fuel use in chipping a trailer. Each trailer was chipped and notes on the weight of the truck and trailer with and without wood were made, likewise truck and chip van combinations were measured before and after dry wood chips were blown into them. Diesel fuel use was calculated on a weight basis by re-filling the chipper fuel tank after each log trailer and recording the change in weight of filling tanks. Time of chipper operation was noted for each trailer. Water use in gallons per minute was monitored with a digital water flow meter. Excess water not used to cool blades in operation passed through the chipper and was not added to the chip van weight. Truck and trailer weights were measure with a truck scale that could accommodate 1 set of axels at each weighing (steering, truck and trailer), the combination of which was the total weight of the truck, trailer and load.
Additionally the yarding truck was weighed at the beginning, middle and end of the chipping day to account for its fuel use and scale drift throughout the day. These weights were used to adjust the measured tractor-trailer weights to reflect the changing values of the tractor weight through the day.

Several truck observations were dropped from this analysis because of transcription errors (low ratio of wood weight on van to trailer weight) and some trailers being chipped without water injection. Two additional trials of green wood (hardwood and pine) are included to widen the range of moisture contents considered in this analysis; most measures made above were included in these green wood measurements as well, except that weights of trucks and vans were calculated from weighing them before and after they delivered loads to a commercial wood energy facility.
Moisture content analysis of the chipped wood was based on several sub-samples of wood from each chipped trailer. Enviva Biomass performed the moisture content analysis in an oven set for 100° C for 24 hours.
Results and Discussion

Calculations of the dry matter content and expected energy content of field dried biomass were made using the sample moisture content. An estimated 8660 BTU/lb higher heating value (HHV) for pine and hardwood was the basis for estimating a lower heating value (LHV) based on microchip moisture content. Using the above values plus throughput information collected in the field, tons, bone dry tons and millions of Btu (lower heating value) were calculated per hour and per gallon of diesel fuel for each of the chipped trailers of green and dry wood. Year, species, piece size and calculated throughput values are displayed in Table 1.

The relationship between these throughput values and the study treatments (species, piece size) and resulting moisture content were analyzed through linear regression. The results of these regressions are displayed in Table 2.

Using the raw throughput numbers as the dependent variable (tons/hour, tons/gallon) produce the strongest, most significant models. The other 4 models (MMBTU/hour, MMBTU/gallon, dry tons/hour, dry tons/gallon) are lower in overall parameter significance and larger squared residuals. Intercept, species and piece size are significant at the $p<.2$ level , while the moisture content is only significant at $p>.5$ except for tons/hour and tons/gallon fuel. The sign of the parameter associated with species indicates that mixed hardwood is more efficient than pine to process (per hour or per gallon) for any measure of throughput considered. The sign associated with piece size indicates that tops plus the first stick of pulpwood is more efficient to process than just tops. One important observation from these analyses is that the moisture content of the material is a relatively poor predictor of machine throughput on a dry matter or energy content basis; piece size and species group are much more predictive. However, the size of the potential impact of the parameter associated with moisture content is can be large; the percent change in throughput from a 50% moisture content to a 20% moisture content ((Y(50% mc)-Y(20% mc)/Y(50% mc))is detailed for each dependent variable in Table 3. For the tons per gallon and tons per hour, an average 33% and 42% increase in throughput can be expected going from 20% MC to 50% MC, for the dry wood tons per gallon and dry wood tons per hour values it is about 6% drop and 3% increase respectively and for the MMBTU/gallon and MMBTU/hour is 27% and 20% drop respectively.

While there are increasing costs related to the production of wood when it is dried (both in weight and energy throughput), these costs may be recouped in a variety of ways. Lower transportation costs (both sourcing range and per ton costs), higher boiler efficiencies and lower storage waste may all counter the increased cost of chipping field dried wood. Only careful study of the whole system of dry wood production and use will determine the real value of the production of dried wood.

References

Steiner, Joseph E., "Comparing Microchips to Conventional Wood Chips", March 14-16, 2011, TAPPI Conference, Atlanta, GA.

Table 1: Treatments and Calculated Throughtput Values by Trailer

Species	Piece Sizes	Year	MC	tons/hour	tons/gal	MMBTU/gallon	MMBTU/hour	dry tons /hour	dry tons /gal
Hardwood	Tops	2011	0.27	26.39	2.06	23.83	305.1	19.19	1.50
Pine	Tops and Logs	2011	0.38	40.51	1.87	17.50	378.4	25.20	1.17
Pine	Tops	2011	0.32	38.09	1.53	16.09	400.7	25.82	1.04
Pine	Tops	2011	0.28	22.61	1.34	15.36	259.0	16.33	0.97
Hardwood	Tops and Logs	2012	0.35	60.92	3.09	31.00	611.1	39.89	2.02
Pine	Tops and Logs	2012	0.26	48.02	2.04	24.06	565.7	35.42	1.51
Hardwood	Tops	2012	0.15	31.60	1.77	25.16	449.2	26.95	1.51
Hardwood	Tops	2012	0.19	34.61	0.82	10.97	461.2	28.06	0.67
Pine	Tops and Logs	2012	0.34	45.02	1.92	19.65	459.8	29.86	1.28
Pine	Tops	2012	0.27	34.58	1.41	16.43	403.8	25.34	1.03
Pine	Tops	2012	0.27	31.45	1.65	19.07	363.7	22.88	1.20
Pine	Tops and Logs	2011	0.37	44.82	1.82	17.41	427.9	28.32	1.15
Hardwood	Tops and Logs	2011	0.46	79.26	2.79	21.17	601.1	42.70	1.50

Table 2: Regression Results for Throughput Calculations by Trailer

RHS	LHS	Parm	P-value	R-squared
tons/gal	intercept	1.15	0.05	0.68
	Species	-0.53	0.04	
	Piece Size	0.51	0.12	
	MC	2.65	0.20	
tons/hour	intercept	17.64	0.13	0.78
	Species	-12.08	0.03	
	Piece Size	13.94	0.05	
	MC	82.46	0.07	
dry tons/gal	intercept	1.37	0.01	0.43
	Species	-0.30	0.11	
	Piece Size	0.36	0.14	
	MC	-0.25	0.87	
dry tons/hour	intercept	26.41	0.00	0.66
	Species	-6.33	0.06	
	Piece Size	10.34	0.03	
	MC	2.87	0.91	
MMBTU/gal	intercept	24.46	0.00	0.37
	Species	-4.38	0.15	
	Piece Size	5.75	0.15	
	MC	-15.31	0.53	
MMTU/hour	intercept	490.62	0.00	0.61
	Species	-87.78	0.08	
	Piece Size	165.55	0.02	
	MC	-251.90	0.52	

Table 3: Impact of Moisture Content on Throughput Variables

RHS	Variables	%Change 50% to 20% MC	average % change
tons/gal	pine top&log	32%	
	pine top	41%	
	hardwood top&log	27%	
	hardwood top	32%	33%
tons/hour	pine top&log	41%	
	pine top	53%	
	hardwood top&log	34%	
	hardwood top	42%	42%
dry tons/gal	pine top&log	-6%	
	pine top	-8%	
	hardwood top&log	-5%	
	hardwood top	-6%	-6%
dry tons/hour	pine top&log	3%	
	pine top	4%	
	hardwood top&log	2%	
	hardwood top	3%	3%
MMBTU/gal	pine top&log	-25%	
	pine top	-37%	
	hardwood top&log	-20%	
	hardwood top	-27%	-27%
MMTU/hour	pine top&log	-17%	
	pine top	-27%	
	hardwood top&log	-14%	
	hardwood top	-21%	-20%

High Tonnage Harvesting and Skidding for Loblolly Pine Energy Plantations

Patrick Jernigan, Tom Gallagher, Mathew Smidt, Larry Teeter[1] and Dana Mitchell[2]

Abstract

The need for alternative and renewable energy sources is evident in the United States to ensure that the nation's energy appetite is fulfilled. The southeastern United States has a promising source for this renewable energy in the form of woody biomass. To meet the energy needs, energy plantations will likely be utilized. These plantations will contain a high density of small stem pine trees. Since the stems are relatively small when compared to traditional product removal, the harvesting costs will increase. The purpose of this research was to evaluate specialized harvesting and skidding equipment that would harvest these small stems cost efficiently. The feller-buncher utilized was a Tigercat 845D with a specialized biomass shear head. The skidder was a Tigercat 630D equipped with an oversized grapple. This equipment was evaluated in a stand with similar characteristics of a southern pine energy plantation. During the study, the feller-buncher achieved an average productivity rate of 52 green tons/PMH and the skidder had an average productivity rate of 123 green tons/PMH. A before tax cash flow model was used to determine a cost per ton for each machine. The feller-buncher costs were $3.48/ton over a 10 year lifespan while the skidder costs were $1.78/ton over the same 10 year life. The results proved that the current system working in a southern pine energy plantation could harvest and skid small stems for approximately $5.26 per ton.

Keywords: harvesting, biomass harvesting

Introduction

The topic of declining fossil fuels and the need for renewable energy sources is evident in today's society. Because of this necessity, researchers and politicians have assembled different ideas in which renewable fuels will be a major part of the United States energy portfolio. Some of the framed ideas include the Billion Ton Report (U.S. Billion Ton Update 2011), "25 by 25" (25x'25), and the Energy Independence and Security Act of 2007. The billion ton report (2011) illustrates how different areas of biomass feedstocks are allocated to the renewable fuel portfolio in a sustainable manner. Another policy that shows promise is the "25 by 25" idea. This states that 25% of our energy consumed must come from biomass by the year 2025. The one policy that has been enacted is the Energy Independence and Security Act of 2007 (EISA). 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

---

[1] Graduate student, Associate Professor, Associate Professor and Professor, School of Forestry and Wildlife Sciences, Auburn University.
[2] Research Engineer, USDA Forest Operations Unit, Auburn, Alabama

of the Act is to have 36 billion gallons of bio-fuels produced annually by 2022. The common attributes of all of these ideas are that they require a tremendous amount of biomass in a relatively short time period. A great deal of this material is expected to be sourced from woody biomass.

Woody biomass is available in such forms as urban residues, mill residues, dedicated energy crops, and logging residues. Currently, mill and logging residues supply the woody biomass market, but they are not sufficient to meet the large scale quantities set forth. Eventually, dedicated energy crops will likely be utilized by the United States to meet the requirements for biomass feedstocks. 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 1998). Studies have been accomplished to determine optimum species, silvicultural techniques, fertilization, genetics, and irrigation to make the crop successful (Tuskan 1998). The barrier with short-rotation woody crops is the immense amount of inputs needed for high growth rates. This poses economic and environmental issues that may hinder the introduction of a biofuel market. These two issues happen to be important considerations when choosing a crop for biomass production. Another aspect that should be taken into account is the volatile risk associated with the biofuel market. The need for biomass feedstocks for energy has not been constant in the past. To mitigate risk, the biomass feedstock crop should be flexible in its ability to produce different products in order for the landowner to make a profit from his/her initial investment. Correspondingly, the crop should be well known in different areas such as management, nursery management, and disease/pest control.

Southern pine stands have the potential to provide significant feedstocks for the biomass energy market (Scott and Tiarks 2008). Pine plantations have played a major role in the success of the forest products industry in the United States but specifically in the southeast United States. The Southeast produces more industrial timber products than any other region in the world (Allen et al. 2005). This can be attributed to the Southeast climate and knowledge of intensive southern pine plantation management. The stands proposed for the energy plantations will predominately be composed of loblolly pine (Pinus taeda) planted at a density between 1000 and 1200 trees per acre (TPA). Stands would be grown for 10-15 years where they will be harvested by the clearcut method. Stands at this age are not merchantable in today's market because of the small stem dimensions at this young age. The shorter rotations will be attractive to landowners looking for a quick return on investment when compared to other timber product types that require much longer rotations.

The problem lies in the logistics of felling the small diameter stems and delivering them to the mill in a form that is economically feasible (Spinelli et al. 2006). Harvesting systems must be balanced for the characteristics of the forest, machine types and intensity of the harvest to reflect the equipment's productivity (Akay et al. 2004). The main issue in the logistics process is the production costs associated with harvesting and handling the smaller stems.

In the Southeast, conventional whole-tree harvesting systems incorporate a feller-buncher to fell and bunch the trees while a rubber-tired grapple skidder drags the bundle of trees to the loading deck (Soloman and Luzadis 2009, Wilkerson et al. 2008). These two machines are essential to the operation and must be productive for profitability. The stems are processed at the loading deck into logs, tree-length material (de-limbed and bucked), or chips. In full tree systems, the residues such as foliage, limbs, bark, and tops are typically left on the loading deck or the skidder distributes the slash back into the harvested stand. These residues, along with the main bole of the tree, provide a large amount of low-cost biomass and potentially hinder future operations such as site preparation (Visser et al. 2009). In an energy plantation setting, the conventional whole-tree harvesting system configuration will follow traditional harvesting techniques and the whole-tree will be chipped. It is essential that the harvesting system be composed of as few machines as possible to save money in maintenance and labor costs, moving costs, and reduced interference delays (Klepac and Rummer 2000). When chipping, the equipment should be utilized to maintain woodflow for the highly productive chipping application. Using a whole-tree chipping system aids the harvesting process in several areas.

Investment in biomass harvesting productivity research studies have been minimal since the late 1980's because of the low interest in biomass feedstocks, resulting in a gap in the understanding of production potential of modern harvesting machines. Based on an unpublished benchmarking study of a current harvesting system operating in south Alabama, the USDA Forest Service found that current felling and skidding costs range from $6.00 to $9.05 per green ton. The use of more specialized and technologically advanced equipment could lower the cost per unit. These systems do not need to be capital intensive to lower costs, but must have the flexibility and capability to be used for conventional round wood production in case of a biomass market collapse. Because of the high volume and low product value, a highly productive operation must be developed to mitigate the low value of the material. High production rates lower the fixed costs by spreading the costs over more units harvested. The system designed for this study is a high-speed, high-accumulation feller-buncher and a modified high capacity rubber tired skidder. Field studies were performed on this new equipment to analyze productivity and costs associated with owning/operating the machines.

Methods

Study Site

Corley Land Services purchased a 10.8 acre stand of 11 year-old timber on a site outside Monroeville, AL to demonstrate the system and implement a production study. The stand used for the study should represent an energy plantation and 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 stumpage acquired had a 10% cruise implemented to get an accurate estimate of the timber inventory on the property. Trees per acre, volume per acre, total volume, average height, and species composition were determined from the cruise.

Production Study

To investigate the feller-buncher engineered by TigerCat, a time study was implemented to understand utilization and production capabilities. Several methods were used to collect data including using a stopwatch, a video recorder, and a MultiDat field recorder.

The productivity of the skidder was evaluated using the same three methods as the feller-buncher time study. First, a stopwatch was used to gather the cycle time for the skidder to leave the loading deck and return with a bundle of felled biomass. These cycle times were analyzed along with the distance traveled per cycle which was obtained by the GPS function of the MultiDat recorder placed in the skidder. Lastly, video was taken to analyze grapple functions and estimate bundle size.

Fuel usage was another variable investigated. The machines were filled in the morning before the operation began. The machines productive hours were measured throughout the day along with the scheduled hours set forth by Corley Land Services. At the end of the day, the machines were filled with a pump equipped with a fuel meter to determine consumption levels.

Results

Based on the cruise data, the average total pine biomass was 87.29 tons/acre. Stand density was measured by trees per acre (TPA) and basal area. Average trees per acre was 576 while the basal area was 120.31 ft2/acre. Other key descriptive stand statistics can be seen in Table 1.

Table 1: Study site density and weight statistics.

	Max	Min	Mean	Standard Deviation	95% lower	95% upper
Basal Area/acre[1]	133.84	95.55	120.32	11.63	111.99	128.64
Trees/acre	660	480	576	54.81	536.79	615.21
Weight/acre[2]	98.15	66.92	87.29	10.15	80.03	94.55

[1]BA/acre=measured in ft^2
[2]Weight/acre=measured in tons

From TPA and tons per acre, average tree size was formulated. Based on the data, average size resulted in 303 lbs or 0.15 tons per tree. This value was utilized in productivity calculations for both the feller-buncher and grapple skidder.

During the study period, a total of 186 feller-buncher cycles were measured and recorded which consisted of the harvest of 1,404 trees. Descriptive statistics for the feller-buncher cycle times are listed in Table 2.

Table 2: Key statistics for feller-buncher cycles.

	N	Min	Max	Mean	Standard Deviation
[1]Acc time	186	0.22	3.48	1.36	0.33
[2]Trees/acc	186	1	15	7.55	2.19

[1]Acc = Accumulation
[2]Acc time = measured in minutes

The mean estimate for time per accumulation was 1.36 minutes (95% confidence interval = 1.30 to 1.42). A scatterplot shows the relationship between the number of trees harvested per accumulation and cycle time (Figure 1). The figure illustrates a trend of increasing cycle time with the increase in trees harvested per accumulation. The average payload per accumulation was estimated at 1.13 tons.

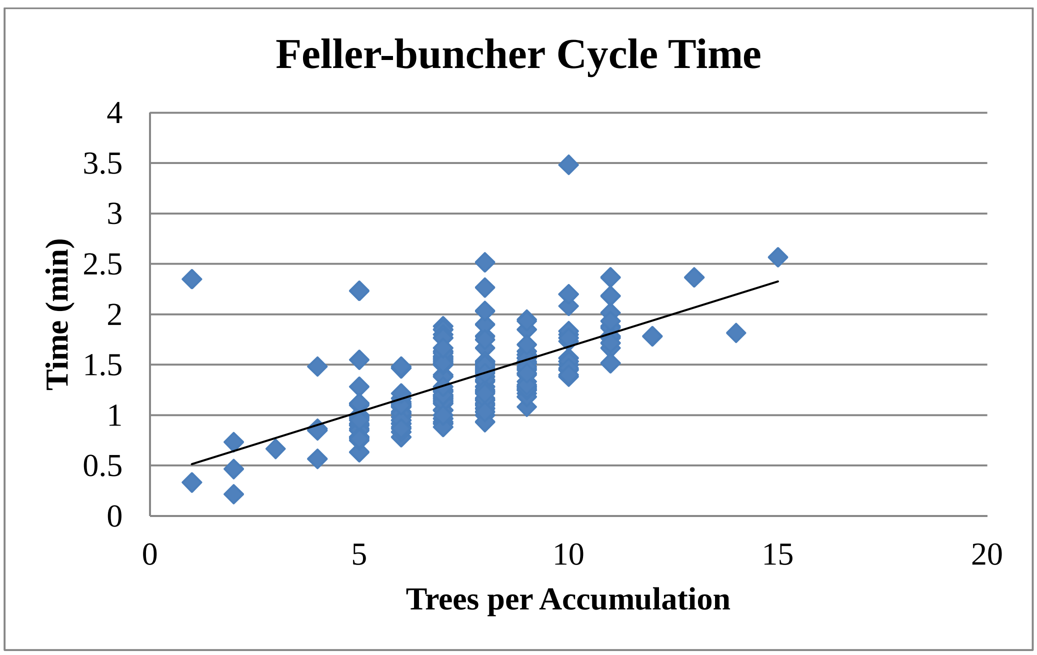


Figure 1: Scatterplot of feller-buncher cycle time versus trees per accumulation.

The feller-buncher productivity was estimated by developing a linear regression model. The response variable was cycle time which was the time to harvest and release one accumulation of trees. The predictor variable was the number of trees harvested per accumulation. The ANOVA table (Table 3) shows that the variability in cycle time is significantly related to the number of trees per accumulation.

Table 3: Analysis of variance for feller-buncher cycle time.

	df	SS	MS	F	Significance F
Regression	1	18.7861	18.7861	67.3571	$3.76157E^{-14}$
Residual	185	51.5971	0.2789		
Total	186	70.3833			

The number of trees per accumulation was proven to be significant using the t-test approach. The following table represents the regression equation details.

Table 4: Regression equation details for the feller-buncher cycle.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%
Intercept	0.300	0.138	2.16	0.031	0.027
Trees	0.144	0.018	8.21	$3.8E^{-14}$	0.109

$$cycletime\ (mins) = 0.14447 trees/accumulation + 0.30044$$

From the table above, the p-value exhibited for the tree variability is statistically significant because it is less than the threshold of 0.05. This indicates that the number of trees harvested is statistically important and explains variability in the feller-buncher cycle time.

To determine skidder productivity, a stopwatch was used to record a total of 59 delay free cycles. The average payload for the delay free cycles was 7.55 tons. Further information concerning delay free cycles is illustrated in Table 5. The relationship between distance and cycle time is displayed in Figure 2 where the graph shows that there is a strong linear relationship between the two variables.

Table 5: Descriptive statistics for skidder delay free cycles.

	N	Max	Min	Mean	Standard Deviation
[1]Cycle Time	59	9:15	1:06	3:55	1:53
Bunch #	59	3	1	1.68	0.502
[2]Distance	59	1096	103	459	251

[1]Cycle time in minutes, seconds
[2]Distance in meters

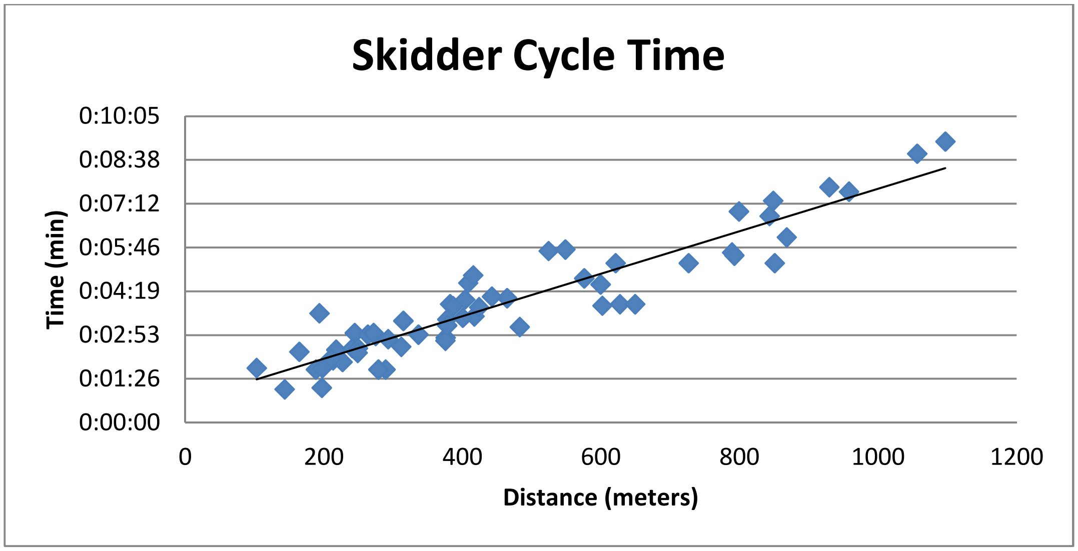


Figure 2: Scatterplot showing delay free cycle time and distance (n = 59 cycles).

From the 59 recorded cycles, a linear regression model was developed for the independent variable cycle time. The regression was proven to be statistically significant at the α = 0.05 level (F-value = 217.9, p-value = $3.8*10^{-27}$). The analysis revealed a high R^2 value of 0.886 and an adjusted R^2 value of 0.882. Thus, distance and the number of bundles explain 88% of variation in cycle time. The ANOVA returned a MSE of $2.04x10^{-7}$. Both independent variables were also proven to be statistically significant at the α = 0.05 level. Indicators for this conclusion are highlighted in red on Table 9. The distance variable was the more significant of the two as shown in the respective p-values calculated (Table 6) and therefore accounts for more of the variance.

Table 6: Regression coefficients and statistical information for the skidder cycle model.

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.0001405	0.000198	0.71	0.4804	-0.00026	0.000537
Distance	4.44437E-06	2.97E-07	14.97	3.13E-21	3.85E-06	5.04E-06
Bunch #	0.000317	0.000141	2.24	0.0286	3.43E-05	0.0006

$$cycletime = 0.000004444dist + 0.00032bunch + 0.00014$$

[1]Cycle time decimal days
[2]Distance in meters
[3]Bunch in number of bunches

Productivity was calculated for each delay-free cycle. Average productivity for the skidder resulted in 123.73 green tons/PMH. The high productivity can be attributed to multiple factors in the study. First, the modified skidder has an oversized grapple which gives it the ability to grapple larger payloads. Since the skidder can acquire more tonnage with each skid without increasing cycle time, the productivity is increased. Also, the tract offered many short skids which minimize cycle time. This is confirmed by the regression developed which showed that distance was the most significant variable. The maximum productivities achieved were when the skidder grappled multiple bunches near the landing. In these cases, the skidder could produce 282 green tons/PMH. This unusually high productivity was not typical in the study. In other situations, long skid distances reduced the productivity to 55 green tons/PMH.

Economic Analysis

Each machine cost was estimated based on production rates found in this study. All costs were input into a before-tax cash flow spreadsheet developed by Dr. Robert Tufts of Auburn University (Tufts and Mills 1982).

The MSRP for a new 845D feller-buncher was acquired from Tigercat. The initial expected capital investment for this specific machine is $495,080. This includes all extra components such as the biomass shear head ($65,945), upgrade on tracks ($5,590), and the Cummins interim Teir IV engine ($18,750). The 630D skidder MSRP was $330,000. For the purpose of this study, a $50,000 down payment was utilized on both pieces of equipment with the rest of the investment financed. Escambia County Bank was contacted for the finance rate and length of loan for the both machines. A typical annual percentage rate (APR) for each machine would be 7% for 60 months (Bill Cox, personal communication, May 2012). Insurance and property taxes were combined as a percentage for the analysis. The insurance (fire, theft, and vandalism) was set at 4% and the property tax rate used was 2%.

All variable costs associated with operating the feller-buncher and skidder were used in the cash flow model. Fuel use was determined based on the detailed records maintained by Corley Land Services. The feller-buncher used approximately 9.9 gallons of off-road diesel per productive/operating hour. The skidder consumed an averaged of 6 gallons per productive machine hour. Off-Road diesel was priced during the study at $3.80/gallon. Lube cost was determined as a percentage of fuel usage (Brinker et al. 2002). These costs were combined in the analysis for a resulting figure of $54.10/PMH for the feller-buncher and $39.16/PMH for the skidder. Repair and maintenance costs were formed using the Caterpillar Performance Handbook. Total repair and maintenance costs were estimated at $16.00/PMH for the feller-buncher. The maintenance and repair rate used for the skidder was $10.00/PMH. If the assumption error is 50%, the overall AEC of the machine had a minimal change (<1%). Major repairs or replacements were also included into the analysis. The two main components that would need to be replaced during the life of the feller-buncher would be the undercarriage and engine. According to Cummins, the feller-buncher engine would need to be rebuilt at year 5 at a cost of approximately $15,000. The undercarriage would have a low rebuild at ages 3 and 9. Also, it would have a major rebuild of the undercarriage at age 6. Both rebuilds include track replacement. Tires (at $8,000 every

3 years) would be the main component with a replacement schedule for the skidder. The labor rate was set at $15.00 per hour with 33% fringe benefits for the operator. An inflation rate of 3% was used on labor, maintenance, and fuel. A utilization rate of 75% was used for the analysis for the feller-buncher instead of the measured 86%. This is the maximum that could be seen for the machine due to expected operational delays. However, the skidder utilization rate of 32% was used because it was limited by the feller-buncher and deck delays.

The annual equivalent cost (AEC) is the cost to own and operate a piece of equipment over its entire lifespan while taking into account the time value of money (Tufts and Mills 1982). For the purpose of this study, the feller-buncher and skidder were placed on a 10 year or 20,000 SMH lifespan. Assuming this ten year span, the feller-buncher has an AEC of $275,066.94. By applying the 52 tons/PMH found in the study to the economic analysis, the feller-buncher could produce a ton of wood for $3.48/green ton. The skidder cost analysis model returned an AEC of $141,323 over the ten year lifespan. By applying the productivity of 123 tons/PMH and an utilization rate of 32% achieved by the skidder, the 630D can skid wood for $1.78/green ton. Thus, the two machines combined can harvest and skid wood for $5.26/green ton before tax in an energy plantation setting.

To better understand the system under government tax rates, an after tax analysis was performed while assuming the same parameters. The marginal tax rate used in the analysis was 25% which was for a married sole proprietor owner tax filing status and having a joint income of $70,700 to 142,700 (CCH 2011). This rate was used because the logger must net this amount of income to pay for the machinery. After applying the federal tax rate, the feller-buncher has an AEC of $206,984 and a cost per ton of $2.62. The skidder's AEC decreased to $106,559 and cost per ton to $1.34. The decrease in cost for both machines reflects a reduction in tax liability due to expenses. These deductions are applied to expenses and interest payments.

Conclusions

In this study, a Tigercat 845D feller-buncher equipped with a biomass shear head was used to harvest and a modified 630D skidder was used to skid the whole trees to the deck. The analysis of the machines took place on an 11 year old pine plantation near Monroeville, AL. The 10.8 acre tract took a total of 22.5 hours to harvest. Production and cost numbers were calculated for each machine working separately. These numbers were further analyzed for prospective system improvements.

The feller-buncher averaged 52 green tons/PMH during the study. Crooked trees, operator inconsistency and lack of experience hindered production. The before tax annual equivalent cost for the feller-buncher was determined to be $275,067 per year. By applying the productivity observed in this study, the cost per ton over a 10 year lifespan would be $3.48. Skidder production was determined to be 123 green tons/PMH. The annual equivalent cost for the skidder was determined to be $141,323. By applying the productivity rates observed in this study, the cost per ton over a 10 year lifespan would be $1.78.

The estimated felling and skidding cost for the two machines in an energy plantation setting is $5.26/ton with a production level of 78,975 tons/year. With improved feller-buncher productivity due to operator experience, production levels could be increased to 106,313 tons/year. This would decrease costs for felling and skidding by $1.08, which would have huge implications on the viability of the system.

This study indicates that the modified equipment met the need of a highly productive system for harvesting young southern pine energy plantations. In addition, the system is flexible in that it can operate in stands with traditional forest product removals to address market fluctuations.

Acknowledgements

This work was partially funded by the Department of Energy under agreement 10-CO-11330132-088. The authors would also like to thank Corley Land Services for their cooperation with this project.

References

25 x `25: America's Energy Future. www.25by25.org/

Akay, A. E., O. Edras, and J. Sessions. 2004. "Determining Productivity of Mechanized Harvesting Systems." Journal of Applied Sciences .Vol. 4(1): 100-105.

Allen, H. L., T. R. Fox, and R. G. Campbell 2005. "What is Ahead for Intensive Pine Plantation Silviculture in the South?" Southern Journal of Applied Forestry Vol. 29(2) pp. 62-69.

U.S. Department of Energy. 2011. U.S. Billion-Ton Update: Biomass Supply for Bioenergy and Bioproducts Industry.

Brinker, R. W., J. Kinard, B. Rummer, and B. Lanford. 2002. "Machine Rates for Selected Forest Harvesting Machines." Alabama Agricultural Experiment Station.

CCH. 2011. 2012 U.S. Master Tax Guide. 95th edition.

Cox, Bill. 2012. Telephone Interview. "Finance Rates for Logging Equipment."

Klepac, J. F. and B. Rummer. 2000. "Productivity and Cost Comparison of Two Different-Sized Skidders." ASAE Annual International Meeting. Milwaukee, Wisconsin.

Scott, D. A. and A. Tiarks. 2008. "Dual-Cropping Loblolly Pine for Biomass Energy and Conventional Wood Products." Southern Journal of Applied Forestry Vol. 32(1) pp. 33-37.

Soloman, B.D. and V.A. Luzadis. 2009. "Renewable Energy from Forest Resources in the United States." New York City, NY: Routledge, 77. Print.

Spinelli, R., E. Cuchet, and P. Roux. 2006. "A new feller-buncher for harvesting energy wood: Results from a European test programme." Biomass and Bioenergy Vol. 31 pp. 205-210.

Tufts, R. A., W. L. Mills Jr. 1982. “Financial Analysis of Equipment Replacement.” Forest Products Journal. Vol. 32(10) pp. 45-52.

Tuskan, G. A. 1998. "Short-rotation Woody Crop Supply Systems in the United States: What do we know and What do we need to know?." Biomass and Bioenergy Vol. 14(4) pp. 307-315.

Visser, R., R. Spinelli, and K. Stampfer. 2009. “Integrating biomass recovery operations into commercial timber harvesting: the New Zealand situation.” Council on Forest Engineering Conference Proceedings: “Environmentally Sound Forest Operations”.

Wilkerson, E. G., B. D. Blackwelder, R. D. Perlack, D. J. Muth, and J. R. Hess. 2008. "A Preliminary Assessment of the State of Harvest and Collection Technology for Forest Residues." Oak Ridge National Laboratory .

Large scale multi-criteria optimization of forestry biomass supply networks

Christian Kanzian[1], Martin Kühmaier[2], Jan Zazgornik[3] and Karl Stampfer[4]

Abstract

For the replacement of fossil fuel forestry biomass should help mitigating Green House Gas (GHG) emissions. However the supply of energy wood is challenging because of high supply costs and rapidly increasing demand. Considering the typical, heterogeneous structure of landownership, contractors and energy producers in Mid-Europe, supply network optimization becomes of major importance. Mathematical supply network optimization often only implies minimizing costs and maximizing profit, respectively. Although the use of forestry biomass affects the GHG balance in a positive way, the supply chain processes cause GHG emissions, which have to be minimized. So there could be a trade-off between maximizing the profit and minimizing GHG emissions within biomass supply networks.

A multi-criteria optimization problem (MOP) has been formulated, whereby the profit must be maximized and the GHG emissions have to be minimized. The network consists of following nodes: (1) sources which represent the roadside stocks, (2) terminals which can be satellite storage locations or freight stations and (3) sinks like power or combined heat and power plants. The objective function includes decision about chipping location, transport mode and volume and terminals used. Typical for MOP there is not a "best" solution, but rather a set of optimal solutions called Pareto optimal points. To solve the MOP the weighted sum scalarization approach was used to derive Pareto optimal points by stepwise changing weights from maximum profit to minimal GHG emissions.
The MOP was applied for a large scale network of approx. 10,000 sources, 356 storages, 119 freight stations and 228 sinks with a demand of 700,000 dry tons. Costs and emissions have been calculated using a digital road and railway network, productivity models and data from literature, respectively. The optimization model was programmed within the optimization suite XpressMP, which is capable for large scale problems.

Putting the weight on minimizing GHG emissions, 30% of the woody biomass should be delivered chipped from the terminals and more than 50% chipped directly from forest causing emissions of 24.3 kg $CO_{2eq*}t^{-1}$ and gaining a profit of 3.0 EUR*t^{-1}. The rest has to be transported solid directly from forest to plant. By changing the weight to maximize the profit GHG emissions will only raise by 4.5%, whereas the profit more than doubles from 3.0 to 7.4 EUR*t^{-1}. Close to

[1] Institute of Forest Engineering, Department of Forest- and Soil Sciences.christian.kanzian@boku.ac.at
[2] Institute of Forest Engineering, Department of Forest- and Soil Sciences
[3] Institute of Production and Logistics, Department of Economics and Social Sciences
University of Natural Resources and Life Sciences, Vienna, Austria
[4] Institute of Forest Engineering, Department of Forest- and Soil Sciences

90% should be supplied chipped from the terminal. The average transport distances will climb up from 45.7 to 48.0 km and 73% of all terminals are used.

Keywords: biomass supply network, multi-criteria optimization, Pareto optimal points, transport mode, terminal allocation

Introduction

The EU policy has fixed an ambitious target for the share of overall energy by renewables, which should reach 20% by 2020 (EU 2009). Depending on the country and its initial position different targets have been set, whereby Austria should reach 34% share of energy from renewable sources in gross final consumption by 2020. In conjunction with that also limits for greenhouse gas emissions (GHG) have been set. Additionally the Energy Efficiency Plan 2011 aims to cut down energy consumptions by 20% by 2020 due to increasing energy efficiency at all stages of the energy chain (EU 2011).

Especially forest biomass for heat and power production got in focus during the last decade in Austria. Promising subsidies for electric power production attracted many companies to invest in combined heat and power plants (CHP). Thereafter usage of woody biomass including black liquor for energy purposes has increased from 14.9 in the year 2005 to 24.3 million m³ solid per annum in 2010 (Nemestothy 2012). However the usage of traditional firewood has a high share of 7.6 m^3a^{-1} solid witch did not changed much over that period, whereas the consumption of forest chips closely doubled from 2.4 to 4.2 million m^3a^{-1}.
Beside this increase of demand also the scale of operation changed, which often has an underestimated impact on the procurement costs. Typically district heating plants had relatively short transport distances up to 30 km for their supply, which was also the recommended economically maximum supply distance in the past. Furthermore Austrian forest stocks mainly in alpine regions and as Spinelli et. al (2012) pointed out that alpine biomass recovery presents two main constraints which are the seasonal access due to snowfall, and the limited availability of a good road infrastructure, respectively. To overcome these shortcomings and to balance the supply all seasons storage terminals can used (Gunnarsson et al. 2004), but procurement costs will be raised (Eriksson and Björheden 1989, Kanzian et al. 2009). Of course storing fresh energy wood has positive effects on the energy content due to natural drying, what has been proven under different location and climates in Europe, respectively (Röser et al. 2011).

Supply chains for energy wood and its processes are studied extensively by a number of researchers in recent years (Talbot and Suadicani 2006, Spinelli et al. 2007, Spinelli and Visser 2009, Eriksson and Gustavsson 2010, Spinelli and Magagnotti 2010, Suadicani and Talbot 2010, Rauch and Gronalt 2010, Harrill and Han 2012, Kong et al. 2012, Spinelli et al. 2012). However different sources of forest biomass, locations of chipping and transport modes lead to a high number of supply chain alternatives (Stampfer and Kanzian 2006) and above mentioned shortcomings show that planning the forest fuel supply is not straight forward task.

Furthermore the typical, heterogeneous structure of landownership, contractors and energy producers like in Mid-Europe leads to a complex energy wood supply network (EWSN) where supply network optimization becomes of major importance. Design of EWSNs and procurement planning for biomass plants attracts worldwide attention, respectively. Common used solution approaches include methods or techniques like discrete-event simulation models, geographic information system (GIS) based models, linear (LP) or mixed integer programming (MIP) or most likely a combination of LP/MIP and GIS (Eriksson and Björheden 1989, Asikainen 1998, Freppaz et al. 2004, Gunnarsson et al. 2004, Ranta 2005, Väätäinen et al. 2005, Perpiñá et al. 2009, Asikainen 2010, Emer 2010, Emer et al. 2011, Kim et al. 2011). Because of its nature, forest biomass is scattered over wide area and therefore these are most of the time location-allocation models. Obviously the spatial distribution of supply and demand has a great impact on the design and costs of a biomass supply network. Therefore, the application of GIS within these studies is very common.

Mathematical supply network optimization often only implies minimizing costs and maximizing profit, respectively. So presents Gunnarsson et al. (2004) a sophisticated MIP model for strategic and tactical planning of an energy wood supply network considering harvest areas, saw mills, terminals, heating plants and seasonal fluctuation over time periods. Applied on a large scale example it has been shown that the objective – minimizing the total cost for the supplier – can be achieved within reasonable time. More recently Emer (2010) developed LP models for transport, multi-period and terminal location problems with the objectives to minimize overall total costs and applied them to several case studies in Italy and Finland. Providing a comprehensive review on forest supply chain network design using mathematical programming, Feng et al. (2010) developed a MIP model for investment decisions on integrating bio-refinery into the forest product supply chain. The multi-period model includes decisions about candidate technologies, facility locations to open, product types, flow quantities and capacities with the objective to maximize the net present value.

Clearly the use of energy wood affects the GHG balance in a positive manner, because GHG emissions are less than those of fossil fuel it replaces (Eriksson et al. 2007). Although especially the transport of forest fuel as a part of the supply chain consumes most of the primary energy (Lindholm et al. 2011) and most likely emits noticeable GHG.

From a live cycle perspective these GHG emissions have to be minimized. So there could be a trade-off between maximizing the profit and minimizing GHG emissions within biomass supply networks. Assuming that these are conflicting objectives this leads to a multiobjective optimization (MO) problem. The generally accepted solution for a MO problem is called a Pareto optimal solution, whereby any improvement in one objective can only be made by worsen at least on one another objective (Messac et al. 2003). This means also that there does not exist a single solution for a MO problem, instead there is a set of Pareto points (Ehrgott 2000).

Although tools for selections of suitable energy wood supply chains for a given condition and a set of objectives are under development (Kühmaier and

Stampfer 2012), MO for a EWSN gives a different perspective and has not really been applied in the design of EWSNs previously, respectively. Moreover to see how sensitive a supply network design reacts on changes on the aims from maximizing the profit to minimizing the GHG emissions a MO model will be formulated and applied on a large scale case study. Beside optimal allocation of energy wood to the heating plants, decisions about chipping location, usage of terminals and transport modes will be included in the MO model.

Materials and methods

Network description

The optimization framework considers a supply network with several nodes, which are forest resources represented as roadside stocks (P), terminals for fuel storage (L), shipping stations for intermodal transport (L) and district heading or combined heat and power plants (H, Figure 1,
Table 1). Decisions about supply networks layout are long term decisions, whereby the considered optimization period is year. Forest resources are limited and site specific (s_i). Generally forest fuel transport mode (K) could be solid (0) or chipped (1) and fuel flows (x_{ijk}) can occur from P to H or from P to H via L at specific costs (c_{ijk}). However transport via shipping stations to plants happens only in transport mode solid, because of the lack of needed unloading equipment for forest chips at existing plants. Solid forest fuel has to be chipped at a point of the supply chain, which could be at the forest landing, terminal or plant. Selection of chipping locations depends on specific chipping costs (hc_i) and according transport costs (c_{ijk}) and will be determined by the optimization model. Typically amounts of biomass at the forest landing are relatively small and account only for 2 to 5 truckloads per site under Austrian conditions (Holzleitner et al., 2012). Therefore the total amount per site has to be either chipped or not to avoid transport of solid and chipped fuel from a single site. This will be ensured by a binary decision variable (z_i). If terminals are opened (y_i) and used, fixed (f_i) and variable (l_{ik}) costs are considered.

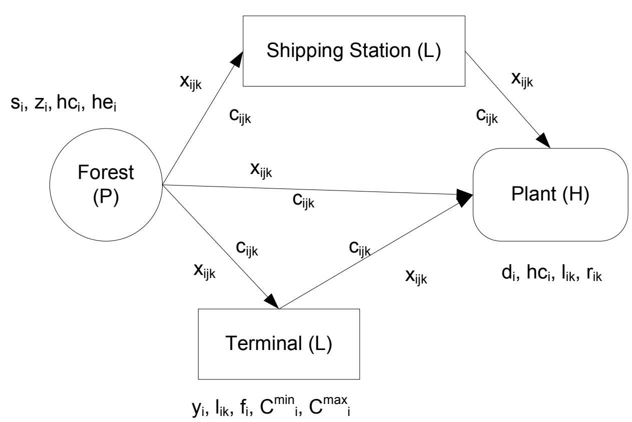


Figure 1. Simplified supply network of forest resources, terminals, shipping stations and plants for the multi-objective optimization model.

Table 1. Used indexes within the multiobjective optimization model.

Notation	Description
P	Set of forest resource points (roadside stocks)
L	Set of terminals and freight stations
H	Set of plants
K	Transport mode – (0) solid or (1) chipped

Table 2. Decision variables used within the optimization model.

Notation	Description
x_{ijk}	Volume to be transported from i to j at mode k, $i \in P \cup L \cup I$, $j \in H \cup L$, $k \in K$
y_i	1, if terminal i should be opened; $i \in L$ 0, otherwise
z_{ik}	1, if chipping is done at i, $i \in P$, $k \in K$ 0, otherwise

Table 3. Data variables used in the multiobjective optimization model.

Notation	Description
s_i	Volume of energy wood at i; $i \in P$
d_i	Demand at i, $i \in H$
he_i	Harvesting costs at i; $i \in P$
hc_{ik}	Chipping cost at i for fuel type k; $i \in P \cup L \cup H$, $k \in K$
r_{jk}	Revenue at j for fuel type k, $j \in H$, $k \in K$
c_{ijk}	Transport costs from i to j for fuel type k, $i \in P \cup L \cup I$, $j \in H \cup L$, $k \in K$
l_{ik}	Variable storage costs at i for fuel type k, $i \in H \cup L$, $k \in K$
f_i	Fixed costs for open terminal i, $i \in L$
C^{min}_i	Minimum turnover of terminal i, $i \in L$
C^{max}_i	Maximum turnover of terminal i, $i \in L$

Multi-objective optimization model

To solve the MO problem and to retrieve Pareto optimal solutions the weighted sum scalarization approach is chosen, where the sum of the two conflicting objectives have to be minimized (1). Under this approach the objective functions are scalarized with nonnegative weights (λ_p, λ_e, Ehrgott 2000), whereby the combination of those weights is extremely decisive for the optimal solution (Stückelberger 2007). Of course as weights can be chosen from all positive real numbers the number of weight combination is infinite. Supposing that the Pareto optimal solutions follow the convexity assumption (Ehrgott 2000), a finite number of 20 combinations will convenient to plot coherent Pareto curves for decision makers. So within these study values for λ_p and λ_e are set in a range from 0 to 1 with an increment of 0.05 (Table 4).

$$\min(x) = \lambda_p \times f_p + \lambda_e \times f_e \qquad (1)$$

Table 4. Weighting factors and functions for the weighted sum scalarization approach.

Notation	**Description**
λ_p, λ_e	Weighting factors for profit and emissions ranging from 0 to 1 stepping 0.05
f_p, f_e	Objective functions for profit (p) and emissions (e)

Objective functions

The first objective function describes the economic point of view of a decision maker, who wants to supply energy wood at the best profit (2). Here the profit results by the sum of the revenues (C^r) minus the sum of the supply costs, which are the harvesting (C^{harv}), transport (C^{trans}), chipping (C^{chip}) and furthermore fixed and variable storage costs (C^{lfix}, C^{lvar}).

$$\max(f_p) = C^r - (C^{harv} + C^{trans} + C^{chip} + C^{l\,\mathrm{var}} + C^{lfix}) \qquad (2)$$

The total amount of the revenue results from two different revenues (k) per plant (p) and the summarized volume transported from forest or terminals to the plants (3). Revenues typically depend on the type of delivered energy wood (solid or chipped) and on the water content, whereby only an average value for the water content is considered.

$$C^r = \sum_{j \in H} \sum_{k \in K} r_{jk} \sum_{i \in P \cup L} x_{ijk} \qquad (3)$$

It is assumed that different harvesting costs (he_i) per forest resource location are part of the supply costs (4).

$$C^{harv} = \sum_{i \in P} he_i \sum_{j \in L \cup H} \sum_{k \in K} x_{ijk} \qquad (4)$$

Chipping cost (hc) depend on the chipping location which can be at the landing, the terminal or the plant, however chipping in the stand is not a widely applied possible option under Austrian conditions and is therefore excluded (5).

$$C^{chip} = \sum_{i\in P\cup L} \sum_{k\in K} hc_{ik} \sum_{j\in L\cup H} x_{ijk} + \sum_{j\in H} \sum_{k\in K} hc_{jk} \sum_{i\in P\cup L} x_{ijk} \quad (5)$$

The sum of transport costs (C^{trans}) are compute as volume flow multiplied by cost for each energy wood type (k) and each used connection (6).

$$C^{trans} = \sum_{i\in P\cup L} \sum_{j\in L\cup H} \sum_{k\in K} c_{ijk} x_{ijk} \quad (6)$$

If terminals are opened (y_i=1) fixed (f_i) costs per year occur (7) and additionally variable costs (l_{ik}) depending on the sum of flows are computed (8).

$$C^{l\,\mathrm{var}} = \sum_{i\in L} \sum_{k\in K} l_{ik} \sum_{j\in H} x_{ijk} + \sum_{j\in H} \sum_{k\in K} l_{jk} \sum_{i\in P} x_{ijk} \quad (7)$$

$$C^{lfix} = \sum_{i\in L} f_i y_i \quad (8)$$

The second objective function deals with the GHG emissions and assures that energy wood will be delivered at minimum emissions, respectively (9). Beside the missing revenue component (C^r) all others are identically to objective function (2) and the component description is the same as described before.

$$\min(f_e) = C^{harv} + C^{trans} + C^{chip} + C^{l\,\mathrm{var}} + C^{lfix} \quad (9)$$

Constraints

The MO model considers a set of constraints, firstly to ensure that the demand will be satisfied (10) and that the resource limits are kept (11).

$$\sum_{i\in P\cup L\cup I} \sum_{k\in K} x_{ijk} = d_j \qquad \forall j \in H \quad (10)$$

$$\sum_{j\in L\cup H} \sum_{k\in K} x_{ijk} \le s_i \qquad \forall i \in P \quad (11)$$

For terminals or shipping stations the energy wood flow must be balanced (12). Depending on the specific terminal minimal (13) and maximal (14) energy wood flows must be met.

$$\sum_{j\in P} \sum_{k\in K} x_{jik} - \sum_{j\in H} \sum_{k\in K} x_{ijk} = 0 \qquad \forall i \in L \quad (12)$$

$$C_i^{\min} y_i \le \sum_{j\in H} \sum_{k\in K} x_{ijk} \qquad \forall i \in L \quad (13)$$

$$\sum_{j\in H} \sum_{k\in K} x_{ijk} \le C_i^{\max} y_i \qquad \forall i \in L \quad (14)$$

As above mentioned typically the amount of energy wood per forest resource location will be limited and to avoid small flows far beyond usual truck loads additional constraints will be added. Constraints (15) and (16) ensure that energy wood is either transported solid or chipped from the same forest location.

$$\sum_{k \in K} z_{ik} = 1 \qquad \forall i \in P \qquad (15)$$

$$\sum_{j \in L \cup H} x_{ijk} \le z_{ik} * s_i \qquad \forall i \in P, k \in K \qquad (16)$$

The decision variable for the energy flows has to be nonnegative, which is mandatory (17). The decision variables for opening of a terminal (y_i) and if chipping should be done at the forest (z_{ik}) can only take value 0 or 1 (18).

$$x_{ijk} \ge 0 \qquad \forall i \in P \cup L, j \in L \cup H, k \in K \qquad (17)$$

$$y_i, z_{ik} = \{0,1\} \qquad \forall i \in P, k \in K \qquad (18)$$

Soft constraints applied within the case study

For the following case study the descripted model could not be applied as it is. Comparing the amount of forest resources and demand within the area, it came up that the energy wood is not sufficient to full fill the demand. As the possibilities and moreover the costs for energy wood imports are unknown and hard to assess, the resource and demand constraints are replaced by "soft constraints". However at least each plant must be supplied with half of its demand (20), but not more than needed (21). Furthermore 90 percentages of the available energy wood resources must be allocated to plants (19).

$$\sum_{i \in P} \sum_{j \in L \cup H} \sum_{k \in K} x_{ijk} \ge 0,9 * \sum_{i \in P} s_i \qquad (19)$$

$$\sum_{i \in P \cup L \cup I} \sum_{k \in K} x_{ijk} \ge 0,5 * d_j \qquad \forall j \in H \qquad (20)$$

$$\sum_{i \in P \cup L \cup I} \sum_{k \in K} x_{ijk} \le d_j \qquad \forall j \in H \qquad (21)$$

Application and case study region

Forest resources, terminal locations and demand

The developed framework and optimization model is applied more or less at a regional level, respectively. The project area covers fife provinces of Austria (Burgenland, Salzburg, Styria, Lower Austria, Vienna) with a total area of 47,200 km² whereby 48% is covered by forest. Each province is split up into forest administrative districts (FAD), whereby 38 of these districts located in the study area. Unfortunately for these districts beside data about growing stock, annual increment and harvest no consistence information on yearly harvestable volume of energy wood does exist. However Gronalt and Rauch (2008) estimate the total available volume of energy wood within the study area to 882,000 oven dry tons (odt), which will be taken as base energy wood resource. As the spatial distribution influences the supply network structure, we need the information about its locations. To map the resources and to represent the resources in the model a square grid of 1.5 by 1.5 kilometer is applied over the forest area resulting in 9,984 resource points. Depending on the forest area of each FAD this means between 31 and 518 points and by dividing the resource volume by the number of points between 33 and 140 odt*a^{-1} (Table 5)

Table 5. By Gronalt and Rauch (2008) estimated potential energy wood supply for the study region and the derived number of supply points by applying a 1.5x1.5 km square grid over the forest area of the 38 forest districts.

Forest district	**Energy wood [odt]**	**points [n]**
Amstetten	21090	194
Baden	13680	151
Bruck an der Mur	37620	479
Burgenland Nord	26790	321
Burgenland Süd	32110	282
Deutschlandsberg	27360	259
Feldbach	15390	110
Graz	35720	281
Gänserndorf	5130	157
Hallein	10640	185
Hartberg	31350	245
Horn	14440	180
Judenburg	32680	328
Knittelfeld	13490	159
Korneuburg	9500	129
Krems	18810	198
Leibnitz	19570	150
Leoben	35150	348
Liezen	29070	454
Lilienfeld	24890	309
Melk	17860	184
Murau	27740	407
Mürzzuschlag	28690	299
Neunkirchen	30780	332
Salzburg	19000	225
Sankt Johann im Pongau	28880	500
Sankt Pölten	18050	167
Scheibbs	27550	256
Stainach	34960	518
Tamsweg	11590	217
Voitsberg	19380	197
Waidhofen an der Thaya	32300	247
Weiz	33440	244
Wien	2470	31
Wien Umgebung	18050	192
Wiener Neustadt	22420	248
Zell am See	22230	514
Zwettl	32300	287
Sum	**882170**	**9984**

The number of heating plants increased stately over the last two decades, but still their does not exist reliable data on plant locations over all Austria. Anyway merging of data provided by the different provinces give us a number of 228 heating and combined heating plants with a heating capacity of more than on MW per plant. Plants with a lower heating capacity than one MW where excluded. All together the energy wood consumption of the selected plants adds up to 982,000 odt*a^{-1}, which means that there is an undersupply if compared to the forest resource potential. Furthermore the energy wood demand is not uniformly distributed over the study region. Larger heating plants with a demand of more than 20,000 odt*a^{-1} accumulated in the east and north and often are located close to the borders of the study area (Figure 2).

An online survey carried out in 2010 discovered that the average water content of the delivered energy wood was 36.8%, whereby this survey included all plant types and sizes. Furthermore there is a clear trend that larger plants take fuel with higher water content (Matzinger 2010). Therefore in all further calculations the average water content will be set to 37.5%.

Due to the lack of data about possible terminal locations a simple procedure in GIS is set up. In general under Austria conditions storing of softwood for longer periods should be avoid because of forest protection against bark beetle. So for different criteria like minimum distances to settlements or coniferous forest and maximum distance to the public road network and a minimal fall of ground a grid layers was calculated in GIS (Kuehmaier et al. 2007). Suitable areas for terminals resulted by weighting and combining these layers. Within these areas approximately every 10 km a terminal point is set, which give a number of 356 terminals (Figure 2). The considered terminals have a minimum construction of one gravel layer with a thickness of 60 cm. On an expected useful life time of 10 years this result in very low fixed costs of 1,100 EUR*a^{-1}. Variable costs per odt are depending if energy wood is solid or chipped and range between 10.4 and 9.5 EUR*odt^{-1}. GHG emissions for the construction work are estimated to be 90 kgCO_{2eq}*a^{-1} as a fixed value if a terminal will be opened and 0.45 kgCO_{2eq}*odt^{-1} per entity transferred via terminals (Table 6).
Within the model framework transport of solid energy wood by railway is included. Trans loading from logging trucks to freight cars happens at shipping stations which are operated by the national railway services (Rail Cargo Austria). Locations of these stations have been provided by them (Figure 2).

Table 6. Terminal data about fixed and variable costs and GHG emissions. [1] Data from Kühmaier et. al (2007).

Description	Values
construction layer	60cm of gravel
capacity [odt*a^{-1}]	200 bis 4000
useful life time [a]	10
storage fixed	
cost [EUR*a^{-1}]	1100[1]
GHG emission [kgCO_{2eq}*a^{-1}]	90.5

	chipped	solid
dry matter loose [% per month]	2.4	0.25
storage period [d]	7	356
storage variable cost [EUR*odt^{-1}]	10.4[1]	9.5[1]
GHG emission [$kgCO_{2eq}$*odt^{-1}]	0.45	0.45

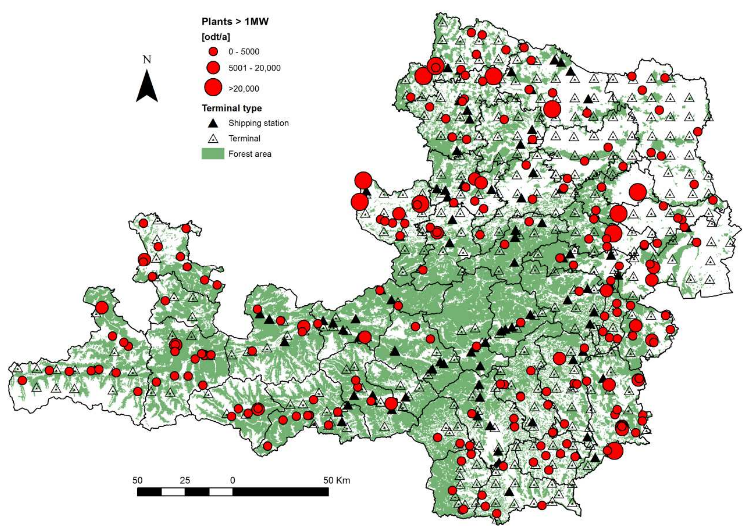


Figure 2. Study area with 38 forest administrative districts, the forest land cover and the locations of heating plants categorized into three sizes.

Revenues, harvesting, transport and chipping costs and GHG emissions

Commonly revenues for EW depend on its water content and accounted per odt nowadays. However based on the official price list of the largest CHP plant of Austria in Vienna the revenues for solid EW will be set to 60 EUR*odt^{-1} and 81 EUR*odt^{-1} for chipped EW.

Principally the harvesting cost could differ for each resource point, but for now the same value for all points is chosen. Taking the results of studies on supply chains in consideration 25 EUR*odt^{-1} and 9 $kgCO_{2eq}$* odt^{-1} seems to be a reasonable values for the harvesting costs and emissions (Affenzeller and Stampfer 2007, Rottensteiner et al. 2008, Sauerzapf 2010). Chipping costs at the roadside will be set to 20 EUR*odt^{-1} and 10 EUR*odt^{-1} at terminals, because at terminals chippers are more productive and moving cost are less. By comparing different literature the GHG emissions seem to be more or less independent on location and chipper model and supposed to be 8.4 $kgCO_{2eq}$* odt^{-1}.

Road transport costs per entity (c_{ifk}) are calculated with formula (22), which includes time associated with transport, loading, unloading and operational delays. It is assumed that the driving time empty and loaded will be the same. So the total transport time is multiplied by the hourly costs and road charges are

added. Finally the costs for one trip will be multiplied by the needed number of trips and divided by the volume per resource point to achieve the costs per entity. The number of trips is calculated by dividing the volume per resource point and the load volume, whereby the result is rounded up to the next integer. For the GHG emissions of the road transport data on GHG emissions per distance are available (Holzleitner et al. 2011, Holzleitner et al. 2012). However, also the number of trips is applied to get more realistic data on road transport emissions.
To achieve the transport costs by rail, the official price list for freight cars is used which contains scaled amounts depending on the distance. So for each shortest shipping station to plant connection the according price is selected and divided by the load volume of the freight car to obtain the cost. GHG emission are based on the values, which are offered by the database of the Global Emission Model for Integrated Systems (GEMIS)
To get the information on driving time, distance and road charges in form of an origin destination (OD) matrix a digital road and rail network was analysed by a using GIS, which provide functions for finding shortest or quickest paths between the network nodes. Taking connections between all described network nodes into account will give an unnecessary huge OD matrix. Keeping the problem size in mind, the maximum drive times were limited to 1 hour from P to L, 2 hours from P to H with a demand <10,000 odt*a^{-1}, 3 hours from P to H with a demand ≥10,000 odt*a^{-1} and from terminals to H.

$$c_{ijk} = \frac{((t_k^L + 2t^D + t^U + 2p_k^W t_k^D)c_k^h + 2c_{ij}^{toll})n_{ik}}{s_i} \qquad \forall i \in P \cup L, \forall i \in L \cup H, k \in K \qquad (22)$$

Table 7. Variables for the transport cost calculations.

Notation	Description
t_k^L	Loading time for mode k
t_{ijk}^D	Driving time from i to j k
t_k^U	Unloading time k
p_k^W	Waiting time as percentage of driving time (t^L) k
c_k^h	Hourly costs k
c_{ij}^{toll}	Road charge from I to j
l_k^V	Load volume for mode k
n_{ik}	Calculated number of trips needed to transport the total volume from i for mode k

Model implementation and Pareto analysis
To solve the MO problem a commercial solver (XpressMP) providing a suitable programming language (MOSEL) is used. However, managing input data and

storing the results of model runs is done with databases. Summarizing and analysing the results is partially done using SQL code within the databases and the statistical software package R (R Development Core Team 2011) with the add-ons RODBC (Ripley 2010), reshape2 (Wickham and Hadley 2007) and plotrix (Lemon 2006). For all spatial tasks like finding terminal and resource point locations, calculating the OD matrixes and map creation ArcGIS with the Network analyst extension is applied.

To do the Pareto analysis and curve the implemented MO model is called with changing the weight parameters and run consecutively by a main programme, respectively. Results of each run are stored in a single database for later analysis. After a solution was found the results of the decision variables were used to calculate the corresponding values with each objective function f_p and f_e separately.

Preliminary results

Due to the large number of constraints (39,778) and variables (1,661,604), which have been reported by the problem statistics of the solver, the memory capacity of the workstation becomes important. Although all 20 run for the Pareto analysis could be solved within acceptable time of approx. 163 minutes in total on a standard workstation, if the tolerance for the integer solution is set to 1%. On the mean the time elapsed to find the MIP solutions was rather short with 130 s (Table 8). The total time includes data in- and output and the computation of the transport cost after formula (22).

Table 8. Basic information on model runs to achieve Pareto optimal solutions.

No.	Weights		Solution	Run time [s]	
	λ_p	λ_e		MIP only	total
1	0	1	16820155	37	480
2	0.05	0.95	15849622	115	392
3	0.1	0.9	14834904	40	321
4	0.15	0.85	13792929	110	488
5	0.2	0.8	12736704	38	377
6	0.25	0.75	11670759	115	484
7	0.3	0.7	10593881	43	371
8	0.35	0.65	9498580	133	415
9	0.4	0.6	8410160	53	466
10	0.45	0.55	7310270	151	510
11	0.5	0.5	6205361	57	474
12	0.55	0.45	5082672	165	464
13	0.6	0.4	3954921	74	514
14	0.65	0.35	2825074	169	449
15	0.7	0.3	1685092	91	511
16	0.75	0.25	540206	330	637
17	0.8	0.2	-603948	211	592
18	0.85	0.15	-1742862	363	725
19	0.9	0.1	-2888861	117	588
20	1	0	-5201650	189	494
Sum				2602	9753

By plotting the results for each objective on x- and y-axes the Pareto curve provides a starting point for interpretation. Trying to keep GHG emissions as low as possible, 30% of the woody biomass should be delivered chipped from the terminals and more than 50% chipped directly from forest (Figure 4) causing emissions of 24.3 $kgCO_{2eq}*odt^{-1}$ and gaining a profit of 3.0 $EUR*odt^{-1}$ (Figure 3). The rest has to be transported solid directly from forest to plant. By changing the weight to maximize the profit GHG emissions will only raise by 4.5%, whereas the profit more than doubles from 3.0 to 7.4 $EUR*odt^{-1}$. Close to 90% should be supplied chipped from the terminal. The average transport distances will climb up from 45.7 to 48.0 km and 73% of all terminals are used.

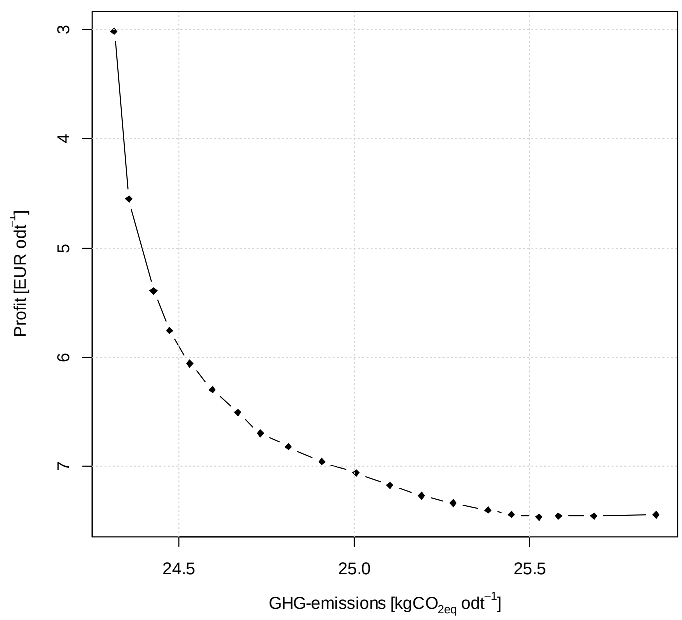


Figure 3. The Pareto curve as a result of 20 model runs with changing weights showing the trade-offs between profit and GHG emission.

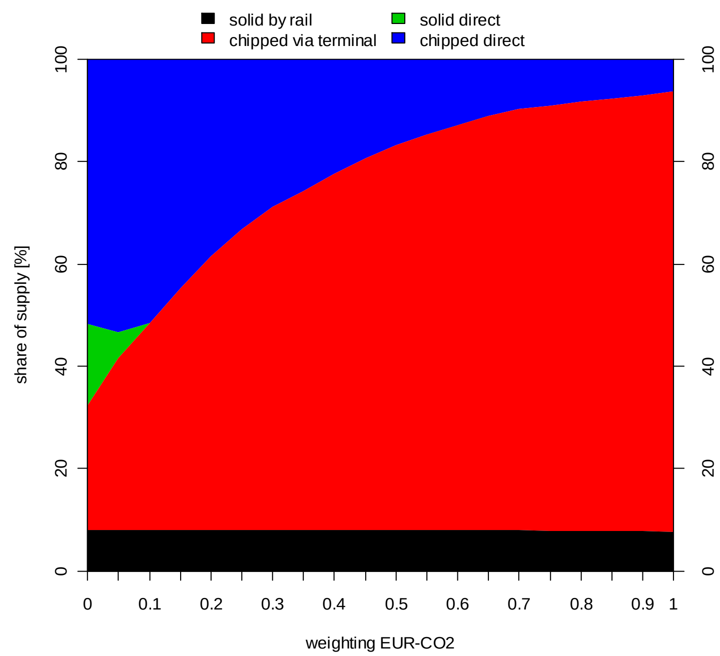


Figure 4. Share of supplied energy wood to the plants split into solid or chipped and its origin depending on the weighting between profit and GHG emissions.

Acknowledgments

The authors would like to thank Austrian Research Promotion Agency (FFG) and Climate and Energy Fund for funding this research project.

References

Affenzeller, G. & Stampfer, K. (2007), 'Energieholzbereitstellung mit Traktor und Krananhänger mit Fallbeilklingenaggregat', Technical report, Institut für Forsttechnik, Universität für Bodenkultur Wien, 29.

Affenzeller, G. & Stampfer, K. (2007), 'Energieholzmehrmengen bei Seilnutzungen im Baumverfahren', Technical report, Institut für Forsttechnik, Universität für Bodenkultur Wien, 30.

Asikainen, A. (2010), 'Simulation of stump crushing and truck transport of chips', *Scandinavian Journal of Forest Research* **25**(3), 245-250.

Asikainen, A. (1998), 'Chipping terminal logistics', *Scandinavian Journal of Forest Research* **13**(3), 386--391.

Ehrgott, M. (2000), *Multicriteria optimization*, Springer, Berlin [u.a.].

Emer, B. (2010), 'Optimization of Wood Energy Plants Supply', PhD thesis, DIPARTIMENTO TERRITORIO E SISTEMI AGRO-FORESTALI.

Emer, B.; Grigolato, S.; Lubello, D. & Cavalli, R. (2011), 'Comparison of biomass feedstock supply and demand in Northeast Italy', *Biomass and Bioenergy* **35**(8), 3309 - 3317.

Eriksson, E.; Gillespie, A.; Gustavsson, L.; Langvall, O.; Olsson, M. & Sathre, R.and Stendahl, J. (2007), 'Integrated carbon analysis of forest management practices and wood substitution', *Canadian Journal of Forest Research* **37**(3), 671-681.

Eriksson, L. & Gustavsson, L. (2010), 'Comparative analysis of wood chips and bundles - Costs, carbon dioxide emissions, dry-matter losses and allergic reactions', *Biomass and Bioenergy* **34**(1), 82 - 90.

Eriksson, L. O. & Bjoerheden, R. (1989), 'Optimal storing, transport and processing for a forest-fuel supplier', *European Journal of Operational Research* **43**(1), 26--33.

EU (2009), 'Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC.', *Official Journal of the European Union* **L 140, 05/06/2009**, 16-62.

EU (2011). http://ec.europa.eu/energy/efficiency/index_en.htm last accessed July 27th. 2012

Feng, Y.; D´Amours, S.; LeBel, L. & Nourelfath, M. (2010), 'Integrated Bio-Refinery and Forest Products Supply Chain Network Design Using Mathematical Programming Approach', Technical report, Interuniversity Research Centre on Enterprise Networks, Logistics and Transportation (CIRRLET), 26.

Freppaz, D.; Minciardi, R.; Robba, M.; Rovatti, M.; Sacile, R. & Taramasso, A. (2004), 'Optimizing forest biomass exploitation for energy supply at a regional level', *Biomass and Bioenergy* **26**(1), 15--25.

Gronalt, M. & Rauch, P. (2008), 'BioLog II - Überregionales Logistik- und Versorgungsnetzwerk für Holz-Biomasse', Technical report, Institut für Produktionswirtschaft und Logistik, Universität für Bodenkultur Wien, 104.

Gunnarsson, H.; Rönnqvist, M. & Lundgren, J. (2004), 'Supply chain modelling of forest fuel', *European Journal of Operational Research* **158**(1), 103--123.

Harrill, H. & Han, H.-S. (2012), 'Productivity and Cost of Integrated Harvesting of Wood Chips and Sawlogs in Stand Conversion Operations', *International Journal of Forestry Research* **2012**.

Holzleitner, F.; Kanzian, C. & Stampfer, K. (2011), 'Analyzing time and fuel consumption in road transport of round wood with an onboard fleet manager', *European Journal of Forest Research* **130**(2), 293-301.

Holzleitner, F.; Kanzian, C. & Höller, N. (2012), 'Monitoring and analysing fuel wood supply processes using a fleet management system', *Submitted to Silva Fennica*.

Kanzian, C.; Holzleitner, F.; Stampfer, K. & Ashton, S. (2009), 'Regional Energy Wood Logistics - Optimizing Local Fuel Supply', *Silva Fennica* **43**(1), 113-128.

Kim, J.; Realff, M.; Lee, J.; Whittaker, C. & Furtner, L. (2011), 'Design of biomass processing network for biofuel production using an MILP model', *Biomass and Bioenergy* **35**(2), 853-871.

Kong, J.; Rönnqvist, M. & Frisk, M. (2012), 'Modeling an integrated market for sawlogs, pulpwood, and forest bioenergy', *Canadian Journal of Forest Research* **42**(2), 315-332.

Kühmaier, M.; Kanzian, C.; Holzleitner, F. & Stampfer, K. (2007), 'Wertschöpfungskette Waldhackgut. Optimierung von Ernte, Transport und Logistik', Technical report, Institut für Forsttechnik, Department für Wald und Bodenwissenschaften, Universität für Bodenkultur Wien, 283.

Kühmaier, M. & Stampfer, K. (2012), 'Development of a Multi-criteria Decision Support Tool for Energy Wood Supply Management', *Croatian Journal of Forest Engineering* **(forthcoming)**.

Lemon, J. (2006), 'Plotrix: a package in the red light district of R', *R-News* **6**(4), 8-12.

Lindholm, E.-L.; Stendahl, J.; Berg, S. & Hansson, P.-A. (2011), 'Greenhouse gas balance of harvesting stumps and logging residues for energy in Sweden', *Scandinavian Journal of Forest Research* **26**(6), 586-594.

Matzinger, H. (2010), 'Versorgungsanalyse von Bioenergieanlagen', Master's thesis, Institut für Forsttechnik, Department für Wald- und Bodenwissenschaften, Universität für Bodenkultur Wien.

Messac, A.; Ismail-Yahaya, A. & Mattson, C. (2003), 'The normalized normal constraint method for generating the Pareto frontier', *Structural and Multidisciplinary Optimization* **25**(2), 86-98.

Nemestothy, K. P. (2012), 'The importance of wood as renewable energy source (in German).', *BFW Praxisinformation* **28**, 5-8.

Perpiñá, C.; Alfonso, D.; Pérez-Navarro, A.; Peñalvo, E.; Vargas, C. & Cárdenas, R. (2009), 'Methodology based on Geographic Information Systems for biomass logistics and transport optimisation', *Renewable Energy* **34**(3), 555-565.

Ranta, T. (2005), 'Logging residues from regeneration fellings for biofuel production - a GIS-based availability analysis in Finland', *Biomass-and-Bioenergy* **28(2)**, 171-182.

Rauch, P. & Gronalt, M. (2010), 'The Terminal Location Problem in the Forest Fuels Supply Network', *International Journal of Forest Engineering* **21**(2), 32-40.

R Development Core Team (2011), 'R: A Language and Environment for Statistical Computing', R Foundation for Statistical Computing, Vienna, Austria, ISBN 3-900051-07-0.

Ripley, B. & from 1999 to Oct 2002 Michael Lapsley (2010), 'RODBC: ODBC Database Access', R package version 1.3-2.

Röser, D.; Mola-Yudego, B.; Sikanen, L.; Prinz, R.; Gritten, D.; Emer, B.; Väätäinen, K. & Erkkilä, A. (2011), 'Natural drying treatments during seasonal storage of wood for bioenergy in different European locations', *Biomass and Bioenergy* **35**(10), 4238-4247.

Rottensteiner, C.; Affenzeller, G. & Stampfer, K. (2008), 'Evaluation of the feller-buncher moipu 400E for energy wood harvesting', *Croatian Journal of Forest Engineering* **29**(2), 117-128.

Sauerzapf, F. (2010), 'Vollmechanisierte Bereitstellung von Waldhackgut im Laubholz – Kosten, Energie- und CO2 -Bilanz', Master's thesis, Institut für Forsttechnik, Department für Wald- und Bodenwissenschaften, Universität für Bodenkultur Wien.

Spinelli, R.; Cuchet, E. & Roux, P. (2007), 'A new feller-buncher for harvesting energy wood: Results from a European test programme', *Biomass and Bioenergy* **31**(4), 205--210.

Spinelli, R.; Lombardini, C. & Magagnotti, N. (2012), 'Annual usage and long-term productivity of a truck-mounted slash bundler under mountain conditions', *European Journal of Forest Research* **131**(3), 821-827.

Spinelli, R. & Magagnotti, N. (2010), 'Comparison of two harvesting systems for the production of forest biomass from the thinning of Picea abies plantations', *Scandinavian Journal of Forest Research* **25**(1), 69-77.

Spinelli, R. & Visser, R. J. (2009), 'Analyzing and estimating delays in wood chipping operations', *Biomass and Bioenergy* **33**(3), 429 - 433.

Stampfer, K. & Kanzian, C. (2006), 'Current state and development possibilities of wood chip supply chains in Austria', *Croatian Journal of Forest Engineering* **27**(2), 135--145.

Stückelberger, J. A. (2007), 'A weighted-graph optimization approach for automatic location of forest road networks', PhD thesis, ETH ZURICH.

Suadicani, K. & Talbot, B. (2010), 'Extracting and chipping hardwood crowns for energy', *Scandinavian Journal of Forest Research* **25**(5), 455-461.

Talbot, B. & Suadicani, K. (2006), 'Road transport of forest chips: Containers vs. bulk trailers', *Forestry Studies* **45**, 11--22.

Väätäinen, K.; Asikainen, A. & Eronen, J. (2005), 'Improving the Logistics of Biofuel Reception at the Power Plant of Kuopio City', *Journal of Forest Engineering* **16**(1), 51-64.

Wickham & Hadley (2007), 'Reshaping data with the reshape package', *Journal of Statistical Software* **21**(12).

Off-Road Transport of Pinyon/Juniper

John Klepac[1] and Bob Rummer[2]

Abstract

A 8-wheel forwarder was observed while transporting pinyon pine (*P. edulis*) and Utah juniper (*J. osteosperma*) from woods to landing in southern Utah. The forwarder was part of a 2-machine system used to treat pinyon-juniper stands. Trees were felled using a rubber tracked skid steer with a shear head, then transported to a collection point with a Ponsse Buffalo King 20-ton forwarder. A total of 47 cycles of the forwarder operating were captured on video and evaluated using time-and-motion study methods. The forwarder averaged 25.8 minutes per cycle at a mean total distance of 786 feet. Total travel distance ranged from 349 to 1851 feet. Total in-woods travel between stops while loading averaged 312 feet per cycle with 7.3 stops. Mean load size was 54.6 trees per load which translated into a payload of 5.08 green tons. The forwarder treated approximately 0.42 acres per hour and had a fuel consumption rate of 3.3 gallons per hour. Forwarding costs and productivity are compared to other alternative methods of off-road transport of pinyon and juniper.

Keywords: biomass, forwarder, time-study, productivity, off-road transport, pinyon, juniper.

Introduction

Pinyon pine (*pinus edulis*) and juniper species *(juniperus spp.)*, often referred to as PJ, are endemic throughout the western US. Miller and Tausch (2001) estimate that over the last 150 years PJ woodlands have expanded tenfold and currently occupy at least 60M ac. Not only has coverage increased, but the density per acre has also increased. There are many negative ecological implications associated with the juniper encroachment and land managers are actively seeking to restore ecological values by removal of PJ. Typical treatments include burning, lop-and-scatter, and some minor utilization for firewood or niche products. Our ability to effect ecological restoration however is limited by the cost of non-removal treatments and lack of viable utilization options.

Because of the widely accepted need for ecological treatment, PJ is a significant potential resource for biomass utilization. The Western Governors' Association assessment of biomass supply (Skog et al. 2008) suggested that PJ accounted for about 1/3 of the available woody biomass (7.5 to 11.5M dry tons per year) in the western US—more than any other single woody feedstock in the region. There are two key barriers however to realizing potential utilization—1) reducing the cost of harvest

[1] General Engineer, USDA Forest Service, Southern Research Station, Auburn, Alabama. jklepac@fs.fed.us
[2] Project Leader, USDA Forest Service, Southern Research Station, Auburn, Alabama. rrummer@fs.fed.us

and processing, and 2) finding conversion processes that are compatible with the properties of this material.

The WGA report estimated the cost of felling, skidding, and chipping PJ at about $70 per dry ton. Most of this cost is a result of low volume per acre and low volume per tree. Extraction (skidding) is often inefficient because of the difficulty of collecting enough volume to make an economically-viable payload. Baughman (2004) timed a grapple skidder and front-end loader system in PJ and found a production rate of about 6 green tons per hour at a cost of about $7 per green ton. The Yankee Group evaluated grapple skidders working in western juniper in Oregon and found productivity ranging from 3.8 to 4.9 green tons per hour with costs up to about $11.50 per ton. Dodson (2010) found skidding costs of $30 to $60 per green ton at a distance of about 450 ft.

There are alternative methods to move material to roadside. For example, one system tested in California chipped trees at the stump and moved chips to roadside using modified forwarders. Another option is to simply increase the payload space/capacity by using large bunks on a forwarder. Both of these solutions are attempting to improve the economics of extraction by increasing the payload volume of the skidding function. The objective of this project was to evaluate the performance, productivity and cost of a large capacity forwarder moving PJ biomass from a woodland restoration treatment. The results are useful in comparing the relative efficacy of alternative approaches to PJ extraction.

Study Location and Treatment

The project is part of a larger treatment area managed by the Bureau of Land Management south of Beaver, Utah. The forwarder test was conducted on approximately 20 acres of generally north-facing slopes in Nevershine Hollow. At this site elevation is 6500 ft (1980 m) above sea level and averages 12-14 inches (305 - 356 mm) of rainfall per year. Mean annual air temperature ranges from 45-48℉ (7-9℃). Slopes range from 5 to 30 percent.

Nevershine Hollow includes about 5500 acres of PJ treatment with tree densities of 100 to over 400 trees per acre. A stewardship contract covered the test units and was designed to: 1) reduce hazardous fuels, 2) restore forest health, 3) reduce tree density and 4) improve biodiversity. The thinning treatment specifies spacing guidelines to leave about 30 small (<8-in dbh) and 8 medium (8 to 18-in dbh) trees per acre. Non-merchantable biomass had to be treated on site to less than 2 feet above ground. Merchantable material was defined as anything larger than 8-in DGL, larger than 3-in top end, or longer than 6 feet and all such material was required to be removed.

---

[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.

The contractor's conventional operation was to use a skid-steer with shear (CAT[2] 297C) in operator selection thinning. Without skidding equipment, the conventional operation was limited to product removal where piles could be created within a reasonable distance of the cutting area. Generally this limited product removal to areas within 200 feet of an access trail or landing.

For this study a large-capacity forwarder was added to the contractor's conventional system. Felling proceeded as normal using the skid-steer shear machines. In some areas the felling operation also created bunches of material by pushing up felled trees. The forwarder operator identified travel paths to best access felled material. On moderate slopes (<20 percent) the forwarder operated relatively freely. As slopes exceeded 20 percent the operator kept travel paths perpendicular to the slope for stability and safety.

A large Ponsse forwarder, a Buffalo King 20-ton forwarder (Figure 1), was selected for this study. To maximize payload the machine had extended bunks (variable load space) that provided an additional 20 percent load space compared to the conventional bunk option (Table 1). This machine was chosen to test the payload capacity of large bunks carrying PJ biomass.

Figure 1. Ponsse Buffalo King 20-ton forwarder.

Table 1. Specifications of large capacity forwarder.

Feature	**Specification**
Engine, horsepower	Mercedes, 275 hp
Total machine weight	22 tons
Tires and tracks	8, Nokian 710/45 (front), 750/55 (rear)
Load space cross-section	64.6 ft^2
Bunk length	16.7 ft w/o extension; 19 ft with extension
Boom reach	31.2 ft maximum

Methods

Productivity and Costs

Operation of the forwarder was recorded on digital video to analyze time study elements. Elements evaluated included travel empty (travel from landing to first in-woods stop), load (swing to pile or tree, grapple and place on forwarder), intermediate travel (travel between piles or trees), travel loaded (travel from woods to landing), and unload (grapple trees in load and place in pile at landing). A Garmin V GPS unit mounted inside the cab recorded traverse data and aided measuring long travel distances. To estimate short travel distances the tires on the forwarder were marked with paint to aid in estimating short travel distances to record the number of revolutions traveled between stops. During loading, the number of swings was recorded along with an estimate of the number of trees and the butt diameter of each tree contained in each swing. For unloading, only the number of swings and trees per swing were recorded.

Machine hours were noted at the beginning and end of each day for estimating gross productivity. Fuel consumption was determined by re-fueling at the end of each day. Acres treated per day were estimated by traversing areas worked each day using a Garmin V GPS unit.

Volume Estimation

As noted above, during loading the butt diameter of each piece was visually estimated. These butt size classes were converted to piece volume using equations developed from this study. The equations converted DBH into volume based on a regression developed from 43 trees sampled from the site. Sample trees were weighed with a Salter Brecknell CS2000 2000-lb capacity digital scale attached to the forwarder boom. Trees were selected to represent a range of diameter classes. For each tree, DGL (diameter at ground line), DBH (diameter at 4.5 feet above ground), crown width, height to the base of the live crown, and total height were recorded. For multi-stemmed trees only DGL was measured. Data from these measurements were used to develop regression equations for estimating whole-tree weights.

Site Disturbance and Soil Moisture

Post-treatment soil surface disturbance was quantified using a point transect method (McMahon, 1995). With this method, soil disturbance was classified at points along transects that were oriented perpendicular to the major direction of forwarder travel. Distance between transect lines was 50 feet and 20 feet between observation points. Compass and pacing were used for direction and distance. Disturbance was classified as either undisturbed, trafficked with litter in place, trafficked with mineral soil exposed, dragged, or deeply disturbed.

Soil samples were collected on four different days for quantifying moisture content. The litter layer was removed and samples were removed to a depth of approximately 2-inches and placed in plastic bags. Samples were weighed wet, dried in an oven at 105 ℃ until a constant weight was obtained and then weighed dry.

Results

Productivity and Costs

A total of 47 cycles were recorded (Table 2). The forwarder treated an average of 3.2 acres/day and averaged 7.6 PMH (Productive Machine Hours)/day. Fuel consumption averaged 25 gallons/day. Occasionally, the skid-steer gathered felled trees and consolidated them into piles. This reduced the number of stops during a cycle, which enhanced the forwarder's production. More than half (53.8%) of the total cycle time was spent loading. A breakdown of the percent of total cycle time required to perform each element is displayed in Figure 2. With a payload of 5.08 green tons the forwarder only hauled 25% of its potential weight capacity.

Table 2. Summary of elementary statistics for the Ponsse forwarder.

Variable	N	Mean	SD	Min	Max
Travel empty (min)	47	3.07	1.161	0.9	6.9
Load (min)	47	13.86	3.450	6.7	25.5
Interm. travel (min)	47	3.25	2.018	0.05	8.6
Travel loaded (min)	47	1.86	0.993	0.6	5.7
Unload (min)	47	3.61	1.091	0.3	5.9
Move during unload (min)	14	0.32	0.661	0.04	2.6
Total time (min)	47	25.75	5.577	14.7	41.7
No. of stops	47	7.3	4.00	1.0	17.0
Travel empty distance (ft)	47	517.4	246.38	175.0	1604.0
Interm. travel distance (ft)	47	312.0	238.85	4.0	1191.0
Travel loaded distance (ft)	47	269.0	145.31	99.0	636.0
Total distance (ft)	47	786.4	331.12	349.0	1851.0
Travel empty speed (mph)	47	1.95	0.510	0.8	3.2
Travel loaded speed (mph)	47	1.68	0.381	1.1	2.7
No. of swings to load	47	20.5	6.11	10.0	39.0
No. of swings to unload	47	9.1	2.26	4.0	15.0
No. of trees	47	54.6	14.94	22.0	93.0
Payload (green tons)	47	5.08	1.395	2.9	8.6
Productivity (green tons/hr)	47	12.1	3.36	6.2	20.5

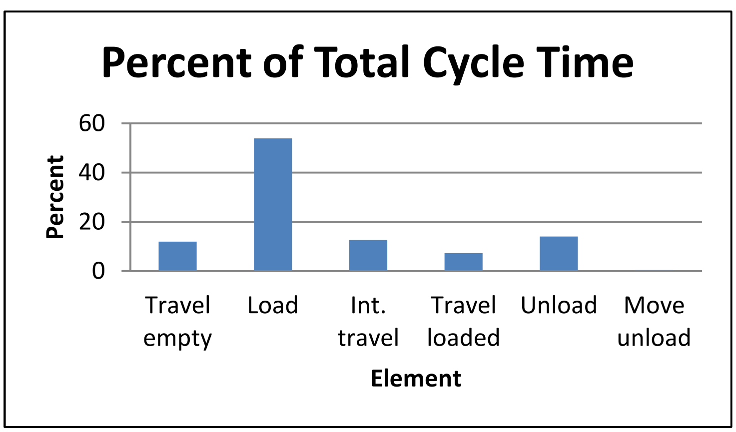


Figure 2. Summary of time study elements for the Ponsse forwarder.

A General Linear Models Procedure (SAS, 1988) was used to determine which independent variables were the best predictors of the dependent variables travel empty, load, intermediate travel, travel loaded, and unload times. These equations are summarized in Table 3.

Loading time started when the machine came to a stop and included all of the activity to collect and load material at a given location. Since the individual trees were relatively light the operator worked to pick up more than one piece at a time. Sometimes this involved bunching pieces together prior to lifting to the bunks. Bunk length and piece size required the operator to build a good payload by careful placement and packing of the material. Each swing was oriented to place the grapple load in the best hole in the payload. The load was built as high as possible above the stakes until the operator judged that additional pieces would not be secure. For loading, the total number of swings required per load and the total number of stems per load were both significant at predicting load time (CV =12.72%, R^2=0.75). Load time increased with more swings and with more stems.

Intermediate travel included all machine movement between stops. It started with wheel movement after the operator secured the boom from the last swing and ended when the machine came to a stop at the next loading location. Generally the operator would be facing the load (the rear of the machine) and driving the opposite direction, looking over his shoulder. The best predictors for intermediate travel time were total intermediate travel distance and the number of stops made during a cycle. The number of stops does not include the first stop made at the end of travel empty, but all stops afterwards. Every 100 ft of intermediate travel added about 30 seconds to the cycle time, every stop adds about 12 seconds. These two factors explained 90 percent of the variability in intermediate travel time (CV =20.26%).

Travel loaded began when the operator left the last stop to travel into the landing. Generally the operator would swing the seat around and drive in a forward-facing position with the boom pressed down on the load to the rear. Travel loaded time was best modeled using travel loaded distance as the independent variable. Because of the load, travel loaded speed was about half of travel empty speed. Every 165 ft of distance added 1 minute to cycle time. For this model, the CV was 25.31%.
At roadside the forwarder unloaded and stacked material into large piles. Piles ranged from 12 to 20 ft tall and 40 to 90 ft long. The best estimate for unload time was the mean value of 3.61 minutes. Confidence interval limits at the 95% level (t=2) were calculated and ranged from 3.29 to 3.93 minutes. Unloading was not affected by the number of pieces in the load or total load volume.

The regression equations in Table 3 were used to estimate productivity as a function of total distance and using mean values for all other variables. A mean of 7 stops, 312-ft intermediate travel distance, 55 stems per load, 20 load swings, and a 5.08 ton payload were used. Using an hourly cost of $91.53/PMH resulted in the cost curve for the forwarder (Figure 3).

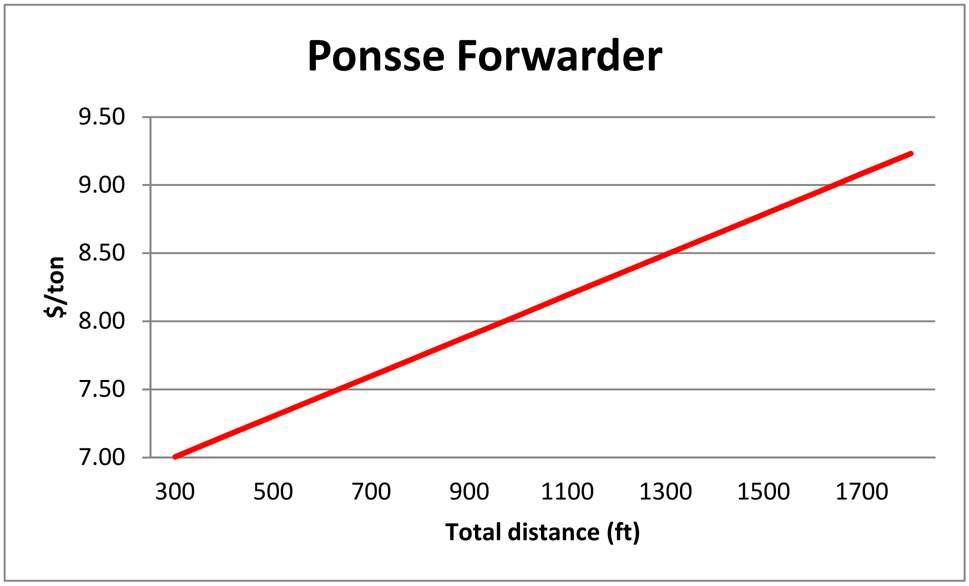


Figure 3. Cost curve for the Ponsse forwarder.

Table 3. Regression equations for predicting elemental times and productivity for the Ponsse forwarder.

Regression equations for time element, (min)	R^2	Mean Square		F Value	Pr > F
		Model	Error		
Travel empty = 0.003842015*tedist[a] + 1.081161	0.66	41.218587	0.46258	89.11	< 0.0001
Load = 0.3509478*lswings[b] + 0.0780867*stems[c] + 2.416484	0.75	205.31166	3.11022	66.01	< 0.0001
IT = 0.00569537*itdist[d] + 0.19817789*stops[e] + 0.02581422	0.90	84.06132	0.43444	193.49	< 0.0001
Travel loaded = 0.00604292*tldist [f] + 0.23092257	0.78	35.470087	0.22074	160.69	< 0.0001

[a]tedist = travel empty distance (ft); [b]lswings = number of swings to load; [c]stems = number of stems loaded;
[d]itdist = intermediate travel distance (ft); [e]stops = number of stops per cycle; [f]tldist = travel loaded distance (ft).

Costs to operate the forwarder were based on a machine rate analysis (Miyata, 1980). These costs reflect the average owning and operating costs over the life of the machine. Using the purchase price, machine life, salvage value, insurance and interest rate, the AYI (Average Yearly Investment) and annual ownership cost was determined. Operating costs were based on machine horsepower, fuel consumption rate, repair and maintenance, tire cost, lube, oil, and fuel cost. Labor cost was calculated using a wage rate per SMH (Scheduled Machine Hours) plus benefits. Data used for these variables are summarized in Table 4.

These data resulted in the costs summarized in Table 5. These costs do not include an allowance for profit and overhead, or consideration of after-tax effects. Using a production rate of 0.42 acres/hr resulted in a transport cost from woods to roadside of approximately $218/ac. With a production rate of 12.1 green tons/hr, transport cost of the forwarder was $7.56/ton.

Table 4. Summary of machine rate input variables for the Ponsse forwarder.

Variable	Input Data
General assumptions	
SMH (Scheduled Machine Hours per year)	2000
Fuel cost ($/gal off-highway diesel)	3.50
Interest rate (%)	10
Utilization rate (%)	90
Ownership variables	
Purchase price ($ - less 8 tires)	430,000
Salvage value (% of purchase price)	20
Insurance rate (%)	1.0
Life (years)	7
Operating variables	
Horsepower	250
Fuel consumption (gal/hr)	3.3
Lube and oil (% of fuel consumption)	6
Repair and maintenance (% of depreciation)	35
Tire cost ($)	30,000
Tire life (PMH)	12000
Labor	
Wage rate ($/SMH)	15.00
Benefits (% of wage rate)	30

Table 5. Cost summary for the Ponsse forwarder.

Item	($US)
Ownership costs ($/SMH)	
Capital	39.63
Insurance	1.41
Total Ownership	41.04
Operating costs ($/PMH)	
Fuel	11.51
Oil and lube	0.69
Repair and maintenance	9.56
Tires	2.50
Total Operating	24.26
Labor ($/SMH)	19.50
Total costs	
($/SMH)	82.38
($/PMH)	91.53

Volume Estimation

A total of 20 pinyon pine and 23 junipers were weighed during the study. Data from measurements of DGL and DBH were used to develop a linear regression equation to predict DBH as a function of DGL. Both species were combined for developing a regression equation to predict load volume based on DBH. Regression analysis showed that DBH squared provided the best prediction of green tree weight and is displayed in Figure 4.

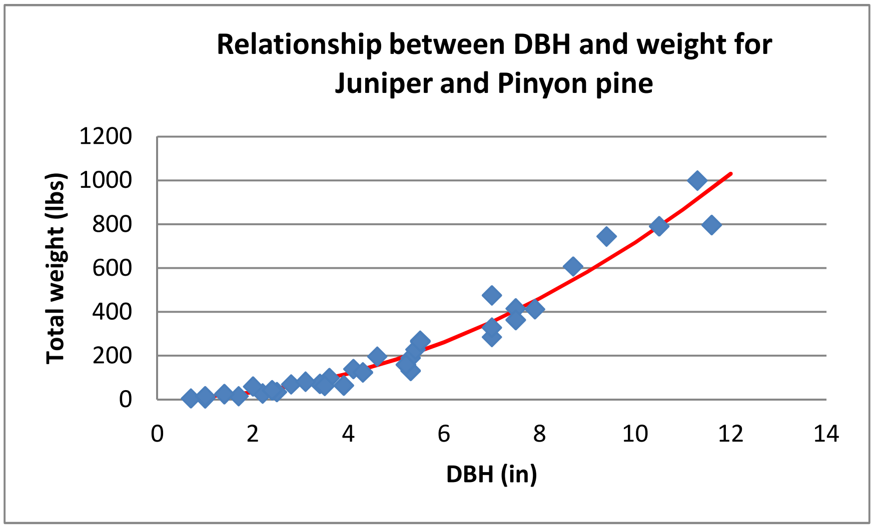


Figure 4. Model to predict total green tree weight as a function of DBH

<u>Model to predict total green tree weight as a function of DBH:</u>

*Weight (lb) = 7.12439304*DBH^2 + 5.01720013*
n = 35; R^2 = 0.96; CV = 21.56%

Site Disturbance and Soil Moisture

A total of 645 observations were collected from the soil disturbance survey. Results of the survey (Figure 5) reflect ground disturbance of the total system; skid-steer and forwarder combined. The system left slightly over one-third of the area (35.2%) undisturbed. Trafficked area totaled 61.4%; 30.1% with litter in place and 31.3% with mineral soil exposed. Only 1.4% of the area had significant disturbance which was classified as deeply disturbed.
Soil moisture content during the operation ranged from 12.5% to 18.9% and averaged 15.7% (oven-dry basis) across the four units.

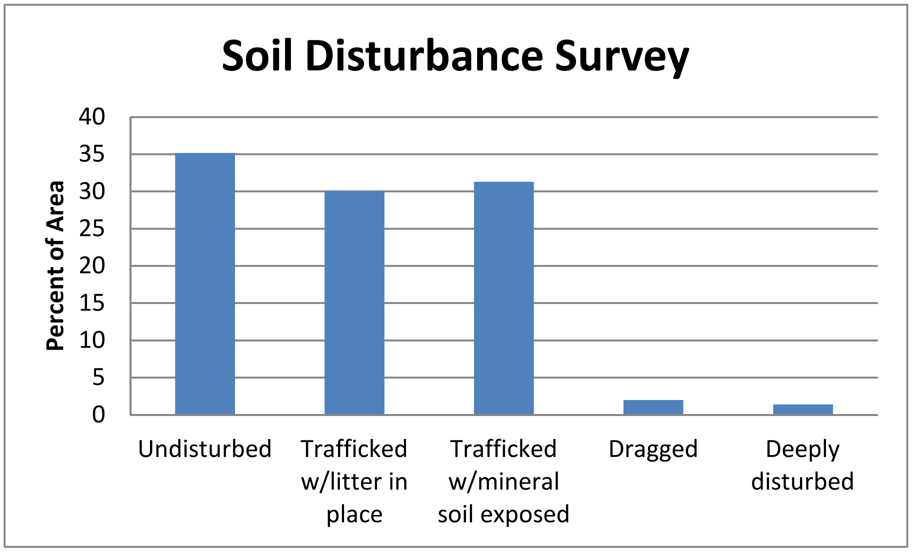


Figure 5. Summary of the soil disturbance survey using the point transect method.

Discussion

The forwarder concept represents one of the simplest approaches to reducing extraction costs to roadside. Bunk volume can be increased by mechanically extending the bunks to each side and by increasing height. In the relatively open PJ thinning treatments overall machine width is not a limiting constraint. This test showed that it is not necessary to add additional bunks to hold short PJ material. Pieces were packed into the load with the crane and the operator demonstrated some skill in achieving large accumulations. Even with the crane packing material with the grapple, the net load density (payload divided by bunk space) was around 9.4 lb/ft^3. This is less than one-half the density of wood chips and just over one-fourth the density of solid wood.

Forwarding productivity is dominated by loading time. Bunched material was loaded in fewer swings and fewer stops and bunching clearly reduces the cost per ton for forwarding. However this comes at the cost of felling productivity. System analysis is needed to ascertain the optimal degree of bunching to minimize total cost to roadside.
Forwarding biomass has a relatively flat cost curve as a function of distance. The longest distance in this study was about 1600 feet and the travel empty time was about 7 minutes. Other forms of biomass extraction that have smaller load sizes are much more sensitive to total extraction distance. This performance attribute of forwarders allows treatments over larger units with fewer roads and landings. A 1600-ft radius from one landing covers an area of 184 acres. It also enhances the concentration of material at the landing to improve the productivity of subsequent chipping and loading. Assuming 10 tons per acre removal a 184-acre unit would have about 1800 green tons of material in one place.

Utilizing a forwarder to transport pinyon/juniper trees from woods to landing appears to have potential as being an effective tool for treating areas under these conditions. Low moisture content of the wood coupled with wide crowns on the juniper trees resulted in a low payload (5.08 tons). Samples collected from trees on a neighboring site revealed wood moisture contents (wet basis) that ranged from 35% to 40%.

Acknowledgements

The authors would like to thank Lance Lindbloom and Bloomin Ranch Service/Southern Utah Biomass Organization, Bureau of Land Management – Cedar City Field Office, Miller Timber Services, Inc., and Ponsse for their cooperation and support during this project. The project was funded by the US Forest Service Washington Office, Research and Development.

References

Baughman, M. 2004. Pinyon-juniper biomass utilization study for Lincoln County, Nevada. Caliente, NV: Lincoln County Regional Development Authority. 20 p.

Brinker, R.W.; Kinard, J.; Rummer, B.; Lanford, B. 2002. Machine rates for selected forest harvesting machines. Circular 296. Auburn, AL: Alabama Agricultural Experiment Station. 29 p.

Dodson, E.M. 2010. A comparison of harvesting systems for western juniper. International Journal of Forest Engineering. 21(1): 40-47.

Grier, C.C.; Elliott, K.J.; McCullough, D.G. 1992. Biomass distribution and productivity of Pinus edulis-Juniperus monosperma woodlands of north-central Arizona. Forest Ecology and Management 50: 331-350.

Matthews, D.M. 1942. Cost control in the logging industry. New York: McGraw-Hill. 374 p.

McMahon, S. 1995. Accuracy of two ground survey methods for assessing site disturbance.
Journal of Forest Engineering, 6(2):27-33.

Miyata, E.S. 19080. Determining fixed and operating costs of logging equipment. Gen. Tech. Rep. GTR CN-55. St. Paul, MN: U.S. Department of Agriculture, Northcentral Forest Experiment Station. 16 p.

SAS Institute Inc., *SAS/STAT User's Guide, Release 6.03 Edition*, Cary, NC: SAS Institute Inc., 1988. 1028 pp.

Skog, Kenneth E.; Patton-Mallory, Marcia; Rummer, Robert R.; Barbour, R. James. 2008. Strategic assessment of bioenergy development in the West. Biomass resource assessment and supply analysis for the WGA region. Final Report. Denver, CO: Western Governor's Association. 38 p.

Ups and Downs Associated with Implementing Shift Schedules on a Southern Harvesting Operation

Dana Mitchell[1]

Abstract

Extended working hours can increase the number of hours that equipment is available to perform work, but how effective are workers during those additional evening/night hours? A study was conducted in Alabama to compare daytime and nighttime production rates of a feller-buncher. The study was installed in a first thinning of a single-aged loblolly pine (Pinus taeda) plantation. A single operator was observed during both daylight and dark hours. Data indicates that the number of stems cut per accumulation was similar between the shifts. However, bunches created during the night shift were smaller than those created during the day and nighttime production was 8.4% less than daytime felling. Further research is needed on this whole harvesting system to determine machine interactions and system performance when implementing shift schedules.

Introduction

The use of extended working hours in the US is not widespread. Those that implement extended working hours cite a variety of considerations that impact their choice of work schedules. Some operate up to 24 hours per day during the winter months to maximize production while the ground is frozen and operable. Cold winter conditions encourage others to schedule more work hours in a day to avoid unproductive time warming engines and fluids. These are two practical responses for addressing environmental conditions through the use of extended working hours.

Extended working hours are also implemented to reduce equipment costs or to increase production. Increasing the scheduled number of working hours should result in increased daily production. Therefore, the cost per ton produced should decrease when these fixed costs are spread over a larger daily production amount.

The daily production increase may not directly reflect the increased scheduled work hours. In other words, the tons per hour produced during the nighttime hours may not be the same as the production rate observed during daytime hours. Ample evidence exists in literature that indicates that there are psychological, physiological and social impacts associated with working longer shifts, or at night (Mitchell et al, 2008). These impacts can result in decreased night shift production, but also in increased safety risks, higher employee turnover, and even increased health risks.

[1] Research Engineer, USDA Forest Service, Southern Research Station.521 Devall Drive, Auburn, AL, USA 36849. danamitchell@fs.fed.us

Production after dark is typically less than the production obtained during daylight hours. In their recent literature review, Murphy and Vanderberg (2007) found that night shift productivity is approximately 10% less than that of the day shift. Nicholls et al (2004) measured a 22% night shift production reduction for in harvester production in first thinnings. In this Australian study, different operators were assigned to each shift, and each shift included hours of daylight and darkness. In a more recent study, Petersons (2010) measured the productivity of a harvester operating in daylight and darkness in first commercial thinnings in Latvia. He found a 12% reduction in the production between daytime and nighttime hours. The harvester performed functions of felling, processing and sorting. The stands contained a mixture of species and trees were not in rows. The objective of this study was to quantify the productivity difference of a single feller-buncher operator working both daytime and nighttime hours in a planted southern pine plantation.

Study Site

The study site was located in Pike County, Alabama, approximately 18 miles from Troy, AL. The 125-acre bedded and planted loblolly pine (Pinus taeda) stand was owned by a large timber landowner. The stand was 15 years old at the time of harvest, and the prescription was a first thinning. To prepare for a nighttime harvest, the contractor chose to fell every fourth row during daylight hours and thin between these rows during the observation periods (day and night). Productivity was compared between day and night conditions with the operator performing the same thinning task.

Methodology

Data was collected, using 1/10 acre plots, to determine the average dbh and height of the trees in the study area. These data were used to determine the descriptive statistics for the study site. A biometric regression equation developed from similar stand data (Klepac, unpublished data) was used to determine the average stem weight based on stem data collected on the site. The study was installed on September 6, 2012. Sunset occurred at 7:02 pm Central Daylight Time (CDT).

Production data were collected on the felling operation during both daylight and dark hours. Data collected included stems per accumulation, accumulations per bunch, and stems per bunch. A stopwatch was used to gather time per accumulation data.

Results

The average stem was 8-inches dbh with a height of 55-feet. The average stem weight was estimated to be 668.26 lbs/tree.

The operator had over a year of experience on the feller-buncher and 24 years of operator experience. The TigerCat 845D was equipped with a standard lighting package with lights mounted on the front and sides of the cab. The cutting head was a shear. This feller-buncher is part of a harvesting system configured specifically to harvest young pine plantations for biomass (Jernigan et al, 2011).

The feller-buncher was observed for a total of 57 accumulation cycles for each shift type (day and night). A cycle was identified as the time it took for the boom to begin to ascend from setting down an accumulation until the boom began to ascend from the next accumulation. Day shift data collection began at 3:35 pm (CDT), and night shift data collection began at 7:56 pm (CDT). Gross time (including short delays) for the day observations was 2 hours, 10 minutes. Gross time for the night observations was 2 hours, 9 minutes. The average accumulation cycle time during the day shift was 2.29 minutes. The average cycle time per accumulation during the night shift was 2.26 minutes. There was no significant difference in the cycle time per accumulation by shift (α=.05, p-value = 0.9363).
The average stems per accumulation by shift differed by an average of 0.72 (Table 1). This difference was not statistically significant (α=.05, p-value = 0.146). The average accumulations per bunch, however, differed by 0.5 (Table 2). This difference was significant (α=.05, p-value = 0.0032).

Table 1. Stems per accumulation per shift

Shift	**N**	**Mean**	**Standard Deviation**
Day	57	7.1	3.1
Night	57	6.4	2.0

Table 2. Accumulations per bunch by shift

Shift	**N**	**Mean**	**Standard Deviation**
Day	28	2.0	0.7
Night	38	1.5	0.6

The operator created 28 bunches during the day shift and 38 during the night shift. The average number of stems per bunch during the day shift was 14.3, while the average during the night shift was 9.5. This difference in the number of stems per bunch was statistically significant (α=.05, p-value < 0.0001). This equates to the night shift operation placing 33.5% fewer stems per bunch than during the day shift.
Using the calculated average stem weight, the night shift produced 121 tons compared to 134 tons produced during the day shift. This translates to 61.55 tons/hr for the day shift, and 56.37 tons/hr for the night shift. Overall, findings indicate a shift difference of 8.4% fewer tons/hr produced during the night shift.

Discussion

While the entire harvesting system was not observed during this short study, we can make some inferences about the impacts of night logging on system productivity. The smaller bunches created during the night shift would potentially negatively impact the production of the skidder. The skidder may have to grapple more bunches to make a full payload, thus increasing the average intermediate travel time between bunches.

The silvicultural prescription of removing every fourth row was not a common prescription for this operator to implement. Removing every fourth row meant that there were three rows to thin between each removal row. The operator was familiar with odd-numbered row thinnings. With even-numbered thinning, the operator thinned two rows on one side and one on other side. While this awkward movement was the same during the day as after dark, it may result in lower overall production as compared to production in odd-numbered row thinnings. During both shifts, the operator would reach out to two rows on either side of the removal row to remove trees that may have been missed while working down the previous removal row.

The feller-buncher used in this study measures 11.1 feet wide. The counter-weight extends beyond the tracks, making it difficult to turn and maneuver in the row (Figure 1). Operationally, the steps required to turn the machine around with a full accumulation to place bunches behind were complex. The operator would set the full accumulator head between the residual trees, walk the track forward, then retract the head and swing the boom around to place the accumulation in a bunch behind the forward rate of progress. The machine was designed for clearcut harvesting, so the production observed in this study may have been negatively impacted by the silvicultural prescription and planting spacing.

Figure 1. Maneuvering is difficult in narrow rows.

The machine did not have an additional lighting package nor any aftermarket lighting added. The operator suggested that lights pointing upward from the cab would have been useful during night felling to avoid hanging accumulated stems in the canopy of the residual stand. Upward pointing lights would have also aided in tree selection for form, as many of the trees in the stand were forked.

The cutting contract required low stumps. The design of the shear allowed the operator to 'bump' the head on the ground before shearing to keep stump heights low. This was made more difficult due to the bedding in the stand. However, the operator stated that he used the same technique to cut low stumps during both shifts.

In discussions with the operator at the end of the night shift, he mentioned that he would not want to work a night shift on a permanent basis. He often arrives to work before sunrise and works in the dark, but that is only on a personal-request situational basis and is not an assigned work schedule. When asked about the isolation of working at night, he responded that he prefers having another equipment operator on site. Even though he doesn't work closely with the skidder operator, they are aware of each other's presence and would check on each other for safety if they hadn't had recent visual contact. In terms of safety, the operator mentioned that he prefers to stay within the safety of the equipment cab at night.

Summary

In this study, the production rate of the feller-buncher during the night shift was 8.4% lower than that of the day shift. However, the production differences were not similar for all feller-buncher functions. The average accumulation cycle time was not different between shifts. In addition, the average number of stems per accumulation did not differ based on shift. The number of accumulations per bunch was found to be significantly different between shifts, which resulted in smaller bunches created during the night shift. These smaller bunches may impact the productivity of the skidding component which was not included in this study.

This short study provides some insight into the impacts of felling trees after dark. Further research is needed on a whole harvesting system to determine machine interactions and system performance when implementing shift schedules.

Acknowledgements

This work was partially funded by the Department of Energy under agreement 10-CO-11330132-088. The authors would also like to thank Corley Land Services for their cooperation with this project.

References

Jernigan, P.; Gallagher,T.; Mitchell, D; Teeter, L. 2011. High Tonnage Forest Biomass Production Systems From Southern Pine Energy Plantations. In: Proceedings of the 34th Council on Forest Engineering annual meeting, Quebec City, Quebec, Canada, June 2011. 6p.

Nicholls, A., L. Bren, and N. Humphreys. 2004. Harvester productivity and operator fatigue: working extended hours. International Journal of Forest Engineering 15(2): 57-65.

Mitchell, D.L., T. V. Gallagher and R. E. Thomas. 2008 The Human Factors of Implementing Shift Work in Logging Operations. JASH 14(4): 391-404.

Murphy, G. and M. Vanderberg. 2007. Modelling the economics of extended shift and 24/7 forest harvesting. NZ Journal of Forestry, August 2007, pp 15-19.

J. Petersons. 2010. Factors affecting harvester productivity in forest thinning in Latvia. In: 16th Annual International Scientific Conference: Research for Rural Development, Jelgava Latvia, May 19-21, 2010: p. 183-187.

Bladed skid trail erosion prediction for the state of West Virginia using USLE and WEPP

Brian C. Morris[1], W. Mike Aust[2], M. Chad Bolding[3]

Abstract

The current West Virginia Best Management Practices (BMPs) system is regulatory in nature; however the effectiveness of the required BMPs is being questioned. The Universal Soil Loss Equation (USLE) and the Water Erosion Prediction Project (WEPP) model were used to estimate differences in potential erosion on bladed skid trails throughout the state of West Virginia. Soil, climate, and terrain variables within the state's six physiographic regions were used as inputs for modeling. Erosion predictions were made using the USLE and WEPP for 15 bladed skid trail closure treatments. Soil cover and surface storage were found to control predicted erosion to the greatest extent. Slash, straw mulch, and grass cover resulted in comparable predicted erosion rates at similar rates of coverage. However, grass coverage relies upon the success of grass establishment on the skid trail surface while mulch and slash are effective when applied. The success of grass establishment may negate any potential erosion control of grass seeding on bladed skid trails. Slash has potential economic advantages and may reduce off road vehicle traffic. The average predicted erosion rate for the 95% slash treatment was 0.2 tons/acre/year while the current BMPs for slopes less than 20% resulted in an average predicted erosion rate of 10.5 tons/acre/year. Overall, these results indicate that outcomes rather than techniques should be used as guidelines for BMP design and implementation.

Introduction

The primary source of water pollution from managed forest lands is sediment (Ice et al., 1997), however the soil loss from roads, trails, and landings are minimal when compared to other land uses (Patric, 1976). The Clean Water Act allowed for the regulation of water pollutants such as sediment from logging operations by individual states. Many states developed Best Management Practices (BMPs) to minimize soil loss and thus minimize water quality degradation from logging operations. Skid trails, roads, and landings are of greatest concern for erosion due to bare soil present in those areas and have been shown to occupy approximately 8-12% of the harvested area in the East (Kochenderfer, 1977; Patric, 1976; Worrell et al., 2010). BMPs which effectively control overland flow of water are able to effectively minimize negative water quality effects (Aust and Blinn, 2004). However the current systems can be improved

[1] PhD Student, brian.morris@vt.edu
[2] Professor of Forestry, waust@vt.edu
[3] Associate Professor of Forest Operations/Engineering, bolding@vt.edu

with improvements in the scientific knowledge, yet to date many BMP programs have not incorporated long term research on the effectiveness of the BMPs (Ice et al., 1997). The effectiveness of BMPs can be quantified using soil loss models (Christopher and Visser, 2007).

A recent ruling by the United States Ninth Circuit Court of Appeals (Fletcher, 2011), which concludes that point sources of pollution from logging operations are not exempt from permitting, has brought national attention to water quality issues resulting from timber harvesting and has left the forest industry concerned about the future of BMP programs. In order to properly address the standards sought with the implementation of the Clean Water Act, soil erosion must be limited through the use of BMPs that are both effective and feasible. This study aimed to determine the effectiveness of current BMPs in West Virginia and determine what management practices may result in a decrease in the potential soil loss from forest harvesting. This was accomplished through the use of the USLE and WEPP. The objectives were:

- Determine erosion potential from bladed skid trails in West Virginia when current BMPS are implemented, and
- Determine the effectiveness of varying levels of grass, straw mulch, and slash in the context of soil loss prevention.

Methods

In order to determine the effectiveness of BMPs currently used in West Virginia and where potential improvements could be made, the USLE (Wischmeier and Smith, 1978) was used to predict erosion from current and potential practices. Upon ranking and statistical analysis of results, subsets were grouped and analyzed using WEPP to confirm predicted results and rankings. Predicted erosion rates for alternative practices were compared with predicted erosion rates from current West Virginia BMPs. BMPs applied to the entire state must provide adequate protection over the entire array of combinations of variables. In order to account for this, mitigation measures were compared for all combinations.

The USLE model was used for initial analysis of variables due to the relative efficiency when modeling 31,122 combinations of variables. The standard USLE equation, (Equation 1) was used. R-values (rain fall erosivity index) ranging from 125 to 175 EI units (100 foot tons/acre) (inches/hour) were used. K-values (soil erosivity index) were determined by NRCS Soil Surveys (NRCS, 2011) for each county in the state of West Virginia. The K-values were rounded to the nearest 0.1 and ranged from 0.1 to 0.6. LS values were based on slope lengths ranging from 40 feet to 100 feet in ten foot intervals and slopes ranging from 5-41% in two percent intervals.

$$\boldsymbol{A = R * K * LS * CP}$$

Equation 1: USLE (Wischmeier and Smith, 1978)

CP-values were derived from thirteen alternative management scenarios and two scenarios representing current BMPs. Due to the inability of USLE to model complex slopes, water bar spacing was accounted for by decreasing the slope length. The management scenarios tested include grass seeding with final grass coverage values of

25%, 50%, 75%, and 95%, straw mulch with coverage of rates of 25%, 50%, 75%, and 95% and the final management scenario includes slash application with coverage ratios of 25%, 50%, 75%, and 95%. CP values were calculated based upon the protocol outlined by Dissmeyer and Foster (1984) which includes factors for the percentage of bare soil, canopy cover, step, on site storage, invading vegetation, and contour tillage practices to determine a total CP value. In order to capture the variability in rainfall, slopes, soil types, and BMPs throughout West Virginia there were three R-values, six K-values, 133 LS-values, and 13 CP-values resulting in 31,122 combinations of variables.

Table 1: Mitigation measures and associated abbreviations tested.

Mitigation Measure	Abbreviation
Water Bar Only	WBO
Grass Seeding 25% Cover	25G
Grass Seeding 50% Cover	50G
Grass Seeding 75% Cover	75G
Grass Seeding 95% Cover	95G
Straw Mulch Application 25% Cover	25M
Straw Mulch Application 50% Cover	50M
Straw Mulch Application 75% Cover	75M
Straw Mulch Application 95% Cover	95M
Slash Application 25% Cover	25S
Slash Application 50% Cover	50S
Slash Application 75% Cover	75S
Slash Application 95% Cover	95S
Current BMPs for slopes < 20%	BMP <20%
Current BMPs for slopes > 20%	BMP >20%

Data Analysis

The erosion prediction values derived using the USLE cover the entire array of potential slopes, slope lengths, K-values, R-values, and management practices. This wide array of data is used to compare the average potential erosion rate resulting from the current BMPs to the potential average erosion rates of the alternatives.

The baseline erosion rates are represented by predicted erosion rates utilizing the mitigation measures outlined by the West Virginia BMP manual (WVDOF, 2005). When all R-values, K-values, and slope values > 20% are modeled using a cover of 50% mulch as described in the manual, the average erosion rate is 13.7 tons/acre/year which is not statistically different ($\alpha=0.05$) than the predicted erosion rate from current BMPs for all slopes < 20% (50% grass cover), 10.5 tons/acre/year. The lack of significant difference between these two scenarios illustrates the adequacy of using the current BMPs as a baseline to determine appropriate measures that could reduce erosion potential.

The current structure of the West Virginia BMPs utilizes mitigation measures designated by slope classification. Due to the current classification, alternative measures were analyzed according to these slope classifications. Analysis of Variance ($p<0.0001$) and a post hoc Tukey-Kramer HSD test were completed to determine what treatments resulted in significantly different erosion potentials. This was completed for all combinations of K-values, R-Values, slopes, and slope lengths as well as all K-values and R-values with slope length held constant at 40 ft and slopes ranging from 5%-19% and again with slopes ranging from 21%-41%.

Results and Discussion

Analysis of treatments for all combinations of variables (Table 2) shows that there is no statistical difference between current BMP measures and these measures are also not statistically different than treatments utilizing 50% slash and treatments using 50% mulch coverage. The erosion protection provided by 95% grass coverage results in a statistically significant decrease in erosion potential with an average of 4.2 tons/acre/year from the current BMP average erosion rates. The subset with the lowest erosion rates included mitigation measures utilizing 95% mulch coverage and 75 and 95% slash coverage.

Table 2: Tukey-Kramer Means Comparison for all R-values, K-values, slopes and slope lengths using Tukey-Kramer HSD. Levels not connected by same letter are significantly different. Alpha=0.05

Mitigation Measure											Mean Predicted Erosion (tons/acre/year)
WBO	A										90.6
25G		B									85.4
50G			C								48.3
25M				D							26.7
25S				D	E						25.1
75G					E	F					21.9
BMP >20%						F	G				13.7
50M							G				12.0
BMP <20%							G				10.5
50S							G				8.8
95G								H			4.2
75M								H	I		4.1
75S								H	I	J	2.2
95M									I	J	0.5
95S										J	0.2

Table 3: Tukey-Kramer Means Comparison for all R-values, K-values, slopes less than 20% and slope length of 40 ft using Tukey-Kramer HSD. Levels not connected by same letter are significantly different. Alpha=0.05

Mitigation Measure						Mean Predicted Erosion (tons/acre/year)
WBO	A					23.5
25G	A					22.1
50G		B				12.5
BMP <20%		B				12.5
25M			C			6.9
25S			C			6.5
75G			C	D		5.7
50M				D	E	3.1
50S					E	2.3
95G					E	1.1
75M					E	1.1
75S					E	0.6
95M					E	0.1
95S					E	0.1

When adjusted for slope, the trends are similar; however, the statistically significant subsets are different. When slopes are less than 20% (Table 3) the differences in potential erosion rates are limited; however, there are still several treatments with lower potential erosion rates than the current BMP measures. The subset with the lowest erosion rates included mulch or slash in excess of 50% coverage or the application of grass seed that will result in ground cover of 95%. Twenty-five percent coverage obtained with the use of slash or mulch as well as grass coverage of 75% produces potential erosion rates less than the current BMPs, however significantly higher than the subset with the lowest erosion rates. Table 4 shows similar trends as slope steepens, however the effect of grass coverage is not as great. The current BMPs produce a lower potential rate of erosion than mitigation measures utilizing as much as 75% grass coverage. Grass coverage of 95% as well as slash and mulch coverage of 75% and 95% remained in the subset with the lowest average erosion potential.

Table 4: Tukey-Kramer Means Comparison for all R-values, K-values, slopes greater than 20% and slope length of 40 ft using Tukey-Kramer HSD. Levels not connected by same letter are significantly different. Alpha = 0.05

Mitigation Measure							Mean Predicted Erosion (tons/acre/year)
WBO	A						102.6
25G	A						96.6
50G		B					54.7
25M			C				30.2
25S			C				28.4
75G			C				24.7
BMP >20%				D			13.7
50M				D			13.7
50S				D	E		9.9
95G				D	E	F	4.8
75M				D	E	F	4.6
75S					E	F	2.5
95M						F	0.6
95S						F	0.2

WEPP Comparison

The use of WEPP to predict soil loss was completed in order to provide a method of comparison to be sure that the results found using the USLE were realistic. WEPP was run for mitigation measures including water bar only, BMPs > 20%, BMPs < 20% and 95% mulch coverage. The scenarios were modeled for slope lengths in ten foot intervals from 40 feet to 100 feet and for slopes in 5% intervals from 5% to 40%. BMP measures were only applied to the slope classes that they are designed for, either < 20% or > 20%, both BMPs were tested at the slope steepness of 20%. K-values were held constant over all iterations at 0.2 and weather data for Charleston, West Virginia was used which has a corresponding R-value of 150. Average predicted soil loss using WEPP for water bars only was 77.5 tons/acre/year while the BMP measures for > 20% slope resulted in an average predicted soil loss of 16.8 tons/acre/year, BMP measures for < 20% slope resulted in an average predicted soil loss of 7.2 tons/acre/year and the use of 95% mulch coverage resulted in an average predicted soil loss of 5.7 tons/acre/year (Table 5). The average predicted soil loss from water bars only was 51.8 tons/acre/year, BMPs > 20% resulted in an average predicted erosion rate of 7.8 tons/acre/year, BMPs < 20% resulted in an average predicted erosion rate of 6.0 tons/acre/year and 95% mulch coverage resulted in an average predicted erosion rate of 0.3 tons/acre/year.

Table 5: USLE and WEPP predicted soil erosion volumes for water bars only, BMP measures > 20% slope, BMP measures < 20% slope and 95% mulch. K-value=2, R-value=150

Mitigation Measure	USLE predicted soil loss	WEPP predicted soil loss
Water Bar Only	51.8 t/a/yr	77.5 t/a/yr
BMP > 20%	7.8 t/a/yr	16.8 t/a/yr
BMP < 20%	6.0 t/a/yr	7.2 t/a/yr
95% Mulch	0.3 t/a/yr	5.7 t/a/yr

The USLE and WEPP results followed similar trends, however the magnitude of predicted erosion differed between the two models. The similar trends shows that the ranking and relative effectiveness of the mitigation measures found during the USLE analysis can be confirmed by WEPP; however, the significance of the differences between mitigation measures is drawn into question due to the differences in predicted volumes produced by WEPP.

Recommendations and Conclusions

The USLE model was able to rank the mitigation measures in a reasonable manner. The ranking was confirmed by modeling using WEPP. Although WEPP requires more detailed data to perform to its full potential, it has been shown that lower levels of data quality are adequate for ranking BMPs (Rhee et al., 2004). Bladed skid trail erosion studies in the Piedmont of Virginia showed that the USLE is an adequate method for ranking BMPs (Wade et al., 2012). This finding was reinforced by the ranking provided by the USLE and the confirmation of this ranking through the use of WEPP.

Current WV BMPs for skid trails on slopes < 20% require grass seeding. This was accounted for in the USLE models; however, the models were run assuming that the grass was established at the coverage rates of 25, 50, 75, and 95%. The time lag between seeding and establishment of grass is not taken into account and could have negative effects on the effectiveness of seed application. Wade et al. (2012) found that when applying 265 pounds per acre of grass seed the resulting surface cover was 45% and in some cases the areas were re-seeded to gain appropriate coverage.

The current BMPs for slopes < 20% were consistently ranked poorly when treatments were separated by slope. This lower ranking suggests that the mitigation measures with a better rank could further reduce erosion rates from bladed skid trails. If the poor ranking was combined with implementation rates and seed establishment rates the effectiveness of the current BMPs would be further decreased.

The results illustrate that the current West Virginia Forestry BMPs do reduce potential erosion; however, there are measures that can further reduce erosion potential. The use of 95% slash on all skid trails could potentially result in an erosion rate < 1 ton/acre/year. Although the erosion of skid trails treated with slash coverage of 95% would effectively reduce erosion, it would only do so if it were implemented. Current BMP implementation rates for grass seeding are approximately 70% (Wang et al., 2007) and BMPs that loggers view as unnecessary will result in the questioning of BMPs and potentially a decrease in implementation (Brynn and Clausen, 1991). The results rank the potential mitigation measures, however do not include any weighting for economic impact of the measures nor is the likelihood of implementation accounted for in this analysis. Swift and Burns (1999) illustrated that there must be balance between the economic cost of the protection and the protection achieved.

In order to reduce the potential for surface erosion from bladed skid trails, canopy must be maintained or created as well as surface cover and storage. Previous research (Luce and Black, 1999) has indicated that there is an inverse relationship between surface cover and potential erosion. Analysis of the USLE output showed that surface cover is very important for erosion prevention. Bladed skid trails are by nature void of surface cover and re-establishment of this cover must be done as quickly as possible to minimize erosion during any establishment period. The application of straw mulch or slash has the potential to accomplish these goals within a time frame that will allow for minimal erosion due to the time lag associated with establishment of grass following seeding.

Average predicted erosion rates were found to be statistically different when separated by slope classes. Harvest planning cannot alter the rainfall patterns of the harvest site; however, harvest planning can take variations in slope and soil type into account. Proper planning could result in decreased erosion by avoiding highly erosive soils or limiting the slope of bladed skid trails. No matter what mitigation measure is used, predicted erosion will be decreased when the measure is applied to a slope that is not as steep or a section where the soil is not as erosive. Proper planning of harvests can have a positive economic impact on the operation. Planning of harvest operations has been shown to be financially viable and reduce the proportion of the harvest area that is disturbed (Kochenderfer, 1977; Krueger, 2004). Decreasing the area of the harvest area in skid trails could also reduce the time required for BMP implementation.

Recommendations:

- Prior to determining what level of protection should be implemented, further research should be conducted to determine what levels of erosion are acceptable.
- The listed results can be used to determine potential resource protection of current and alternative BMPs, however any change must be justified economically as well and environmentally.
- Increasing surface cover and storage will reduce potential erosion rates.
- Proper planning to minimize the slope of skid trails as well as planning properly for the rainfall patterns and soil type present will result in decreased potential erosion.

For the protection of resources, the use of 95% slash would be ideal. Prior to this being implemented as a new BMP requirement the economic costs and benefits must be analyzed as well as the likelihood of implementation. If loggers and landowners find that this requirement is not necessary and do not implement the new BMP, the erosion potential could become greater than the current BMP format due to non-compliance.

Literature Cited

Aust WM, Blinn CR. Forestry Best Management Practices for Timber Harvesting and Site Preparation in the Eastern United States: An Overview of Water Quality and Productivity Research During the Past 20 Years. Journal of Water, Air and Soil Pollution (2004) 4:5-36.

Brynn DJ, Clausen JC. Postharvest Assessment of Vermont's Acceptable Silvicultural Management Practices and Water Quality Impacts. Northern Journal of Applied Forestry (1991) 8:140-144.

Christopher EA, Visser R. Methodology for Evaluating Post Harvest Erosion Risk for the Protection of Water Quality. New Zealand Journal of Forestry (2007) 52:20-25.

Dissmeyer GE, Foster GR. A guide for predicting sheet and rill erosion on forestland. (1984) USDA For. Ser. Gen. Tech. Publ. R8-TP 6. 40p.

Fletcher WA. Northwest Environmental Defense Center v. Brown. In: No. 07-35266--Circuit USCoAftN, ed. (2011). 44.

Ice GG, Stuart GW, Waide JB, Irland LC, Ellefson PV. Twenty-Five Years of the Clean Water Act: How Clean Are Forest Practices? Journal of Forestry (1997) 95:9-13.

Kochenderfer JN. Area in Skid Roads, Truck Roads, and Landings in the Central Appalachians. Journal of Forestry (1977) 75:507-508.

Krueger W. Effects of future crop tree flagging and skid trail planning on conventional diameter-limit logging in a Bolivian tropical forest. Forest Ecology and Management (2004) 188:381-393.

Luce CH, Black TA. Sediment production from forest roads in western Oregon. Water Resources Research (1999) 35:2561-2570.

NRCS. Web Soil Survey (2011) Washington, DC: Natural Resource Conservation Service, United States Department of Agriculture. http://websoilsurvey.nrcs.usda.gov.

Patric JH. Soil Erosion in the Eastern Forest. Journal of Forestry (1976) 74:671-677.

Rhee H, Fridley JL, Foltz RB. Modeling erosion from unpaved forest roads at various levels of geometric detail using the WEPP model. Transactions of the ASAE (2004) 47:961-968.

Swift LW, Burns RG. The Three Rs of Roads: Redesign, Reconstruction, and Restoration. Journal of Forestry (1999) 97:40-44.

Wade CR, Bolding MC, Aust WM, Lakel III WA, Schilling EB. Comparing Sediment Trap Data with USLE-Forest, RUSEL2 and WEPP-Roads Erosion Models for Evaluation of Bladed Skid Trail Best Management Practices. Transactions of the ASABE (2012) 55(2):403-414.

Wang J, McNeel J, Gogg W, Milauskas S. Assessment of Compliance of Forestry Best Management Practices in West Virginia. Southern Journal of Applied Forestry (2007) 31:60-65.

Wischmeier WH, Smith DD. Predicting rainfall erosion losses: A guide to conservation planning. (1978): Science and Education Administration, USDA. Agricultural Handbook no. 537. 58p.

Worrell WC, Bolding MC, Aust WM. Comparison Of Potential Erosion Following Conventional And Cable Yarding Timber Harvests in the Appalachian Plateau

Region of Virginia. In: 33rd Annual Meeting of the Council on Forest Engineering: Fueling the Future--Mitchell D, Gallagher T, eds. (2010).
WVDOF. West Virginia Silvicultural Best Management Practices for Controlling Soil Erosion and Sedimentation from Logging Operations (2005) Charleston, WV. 31.

FORECASTING AND MONITORING MOISTURE CONTENT OF WOODY BIOMASS IN IRELAND AND OREGON TO IMPROVE SUPPLY CHAIN ECONOMICS

Glen Murphy[1], Francisca Belart[2], Tom Kent[3] and Pieter D. Kofman[4]

ABSTRACT

Wood is approximately 50 percent water by weight. Reducing the amount of water, through drying, reduces transportation costs (more wood and less water can be delivered per load) and increases combustion efficiency (less energy is required during combustion to evaporate water).

Researchers in Ireland and Oregon are collaborating on storage and drying research on a number of fronts:

(1) they have completed, air-drying trials for three softwood and two hardwood species at seven locations. The trials will allow the development of climate based drying models for forecasting drying rates for different species, for different seasons of the year in different locations within their regions.

(2) a number of moisture monitoring tools, using a variety of technologies, are being evaluated for their efficiency and effectiveness in measuring moisture in a range of materials such as roundwood, chips, hogfuel, and bundled biomass in twelve species. Some of the same tools are being evaluated in both Oregon and Ireland.

(3) an economic model, that spans the supply chain from standing tree through to delivery to the customer and includes the effects of moisture management on costs and revenues, has been developed.

An overview of the research and preliminary results are included in this paper.

INTRODUCTION

Biomass dependency has been increasing gradually and is currently over 4 percent of U.S. total energy consumption (Energy Information Administration 2010). Half of this biomass energy consumption comes from wood sources; wood residue, wood waste, and woody plants.

High production and transportation costs, relative to market values, can be economic barriers to the widespread utilization of woody biomass for energy production. Moisture management, through storage and drying in the supply chain between harvesting and utilization, is key to improving both transportation costs and market values (Jirjis 1995).

[1] Oregon State University, USA
[2] Oregon State University, USA
[3] Waterford Institute of Technology, Ireland
[4] Danish Forestry Extension, Denmark

Wood is approximately 50 percent water by weight. Reducing the amount of water, through drying, reduces transportation costs (more wood and less water can be delivered per load) and increases combustion efficiency (less energy is required during combustion to evaporate water). Moisture can be actively reduced through input of energy at an off-forest facility, or it can be passively reduced through air-drying on- or off-forest. Air-drying is generally the more common and lower cost alternative.

Managing woody biomass moisture requires tools for forecasting and monitoring drying rates and determining, in economic terms, when is the best time to cease drying and deliver the biomass to the customer (Fauchon et al. 2004). Quick, accurate and simple methods of determining moisture content along the supply chain will facilitate trade by reducing risk.

Researchers in Ireland and Oregon are collaborating on storage and drying research on a number of fronts. An overview of the research being undertaken and preliminary results on climate based drying models, moisture monitoring tools, recommended sampling protocols, and economic analyses of woody biomass supply chains is presented below.

METHODS

Supply Chain Economic Models

Supply and utilization of biomass as an energy source must be economically competitive for both buyers and sellers if its contribution to meeting energy needs is to be viable in the long term. Evaluating economic competitiveness can be complex. Harvesting biomass crops, collecting biomass residues, and storing and transporting biomass resources are critical elements in the biomass resource supply chain.

In 2010 the Irish Council on Forestry Research and Development group (COFORD) commissioned two of the authors of this paper (Kofman and Murphy) to develop two tools to help small wood energy businesses evaluate supply chain economics: a Fuel Cost Comparison Tool, which as the name suggests allows comparison of the costs of fuel alternatives by fuel users, and a Wood Fuel Value Calculator, which allows wood energy sellers to compare the net value alternative wood supply systems.

Both models were developed as stand alone programs in Visual Basic. User's manuals were also prepared. Training in use of the models has been provided to wood energy providers in Ireland and Europe.

Use of the models affirmed the importance of having good measures of the moisture content of the energy material to be supplied.

Drying Trials

Six air-drying trials were established at six sites; two of the sites were in Ireland and four in Oregon. Three softwood species (Sitka Spruce, Lodgepole pine and Douglas-fir) and two hardwood species (Eucalyptus nitens and hybrid poplar) were included in the trials.

Daily or hourly climate data was collected at each site. Moisture content related data was collected on a regular basis.

The first Irish trial was begun in April 2007 and was ended over 450 days later. Bins of small diameter Sitka Spruce logs (approx. 25 tons), resting on load cells were monitored hourly for changes in weight that were assumed to be related to changes in moisture content. Samples of the logs were taken at the beginning of the trial to establish initial moisture content. The trial included five treatments that related to wood size (two classes) and cover (three classes). Some bins were followed for the full 450 days, others were terminated early then reloaded with new logs to assess the effects of changes in the season in which trees were felled and drying began. The data from the first trial was used to develop climate related air-drying models.

The second Irish trial was begun in March 2011 and was continued for 12 months. Bins of small diameter Sitka Spruce, Lodgepole pine and Eucalyptus nitens logs (approx. 25 tons) were monitored for changes in weight. The trial included two treatments; covered and uncovered logs. The trial was used to determine differences in drying rates between species and to confirm the impact of cover on drying rates.

Two Douglas-fir drying trials were begun in northern (wet site) and southern (dry site) Oregon in December 2010. The trial continued for 12 months. Drying trials were initiated four times at each study site At each trial, three bundles were built (about 3 m long and with an average log diameter of about 156 mm) and each bundle was air dried under different canopy conditions: open, intermediate, and closed. A total of 24 Douglas-fir biomass bundles were built over the study period and the average initial weight of the bundles was about 2,261 kg. Bundles were weighed using crane scales on regular intervals (approx. 10 days). The data from these trials was used to develop climate related air-drying models for Douglas-fir.

Two hybrid poplar drying trials were begun in western (wet) and eastern (dry) Oregon in April 2011. The trial continued for 9 months. At each trial, two different types of bundles were built: denoted as small and large. The small hybrid poplar bundles consisted of logs with average diameter of 82 mm. The average initial weight of the small bundles was about 3,444 kg. The large hybrid poplar bundles consisted of logs with an average diameter of about 150 mm. Their average initial weight was about 5,413 kg. A total of 8 hybrid poplar bundles were built over the study period; 4 small poplar bundles and 4 large poplar bundles. Bundles were weighed using crane or truck scales on regular intervals (approx. 10 days). The data from these trials was used to develop climate related air-drying models for hybrid poplar.

Evaluation of Monitoring Tools

Evaluations were undertaken in Ireland and Oregon of three classes of tools for monitoring moisture content in woody material; capacitance, conductance (or resistance) and acoustic tools. A total of nine species (five softwood and four hardwood) and four material types (small logs, chips, hogfuel and slash bundles) were included in the trials. Not all tools were evaluated in all species or material types.

Capacitance tools evaluated in Ireland were Wile Bio Meter, Humimeter BM1, Humimeter BLL, and GE Balemaster. All four capacitance tools were evaluated in chips but only the Wile Bio Meter and Balemaster were evaluated in slash bundles. Conductance tools evaluated in Ireland were the Humimeter BLW and the GE Timbermaster. Conductance tools were used for measuring the moisture content of small logs. No acoustic tools were evaluated in Ireland. Tools were evaluated in Sitka Spruce, Lodgepole pine and Eucalyptus nitens.

Capacitance tools evaluated in Oregon were Wile Bio Meter and Humimeter BM1. Both capacitance tools were evaluated in. Conductance tools evaluated in Oregon were the Humimeter BLW and the GE Timbermaster. Acoustic tools were the Fiber-Gen HM200 and the IML Hammer. Both conductance tools and acoustic tools were used for measuring the moisture content of small logs. Tools were evaluated in Douglas-fir, Western hemlock, Ponderosa pine, hybrid poplar, Garryana oak, and madrone. Samples were repeatedly measured from freshly felled material to dry material over a four month period at regular intervals – four day intervals for chips and hogfuel and 10 day intervals for small logs.

Tools were evaluated in terms of accuracy, precision, mechanical reliability and efficiency (total time required to obtain a mean measurement within a stated accuracy range).

RESULTS AND DISCUSSION

Supply Chain Economic Models

The Wood Fuel Value Calculator that was developed requires data related to purchase type (standing tree, roundwood or chips); wood data (basic density, volume conversion factors, ash content); moisture content at various points in the supply chain; harvesting costs, chipping costs and storage information; transport (hourly costs, trucking distances, load volumes, unloading method); and price, profit and interest. Conversion between different units of measurement at various points in the supply chain can be easily accommodated.

Figure 1 provides an example of a completed form. In this example, hardwood trees with a basic density of 490 kg per m^3 were purchased standing in the forest for €10.50 per m^3, then felled, extracted to roadside and chipped in the forest for a total of €23 per m^3. Chipped material had a moisture content of 50% (wet basis). Chipped material was then transported in 90 m^3 (loose volume) vans to a customer 80 km away from the forest. The customer was prepared to pay €6.45 per GJ for the delivered material. A net value of -€3.23 per ton of delivered material would be incurred. The supplier would either to reduce his profit goal substantially (from 9.00% to 2.75%) or look at other approaches, such as drying the material in the forest.

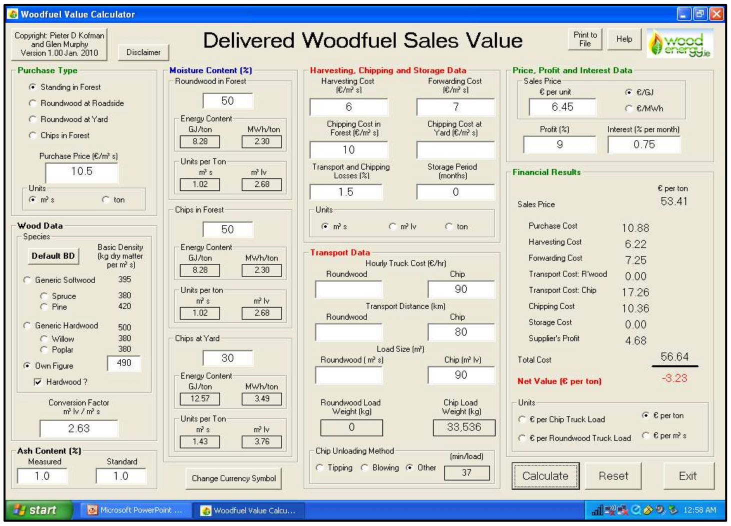


Figure 1. Completed screen for the Wood Fuel Value Calculator

If the felled and extracted timber had been left at roadside in the forest to dry for five months, reaching a moisture content of 30% before it was chipped, net value would have gone from negative to positive (€0.38 per ton) despite the system incurring additional chipping costs (allowing for additional wear on chipping knives) and storage costs. The supplier would also achieve his 9% profit goal.

Drying Trials

The first drying trial in Ireland allowed the development of an air-drying model based on climatic conditions (precipitation and reference evapotranspiration) and treatment (material type and cover type). Figure 2 shows that the forecast number of days to dry depends on where drying takes place in Ireland when drying begins in summer. If drying is delayed three months, to the beginning of autumn, drying could be expected to take an additional 66 to 101 days depending on drying location.

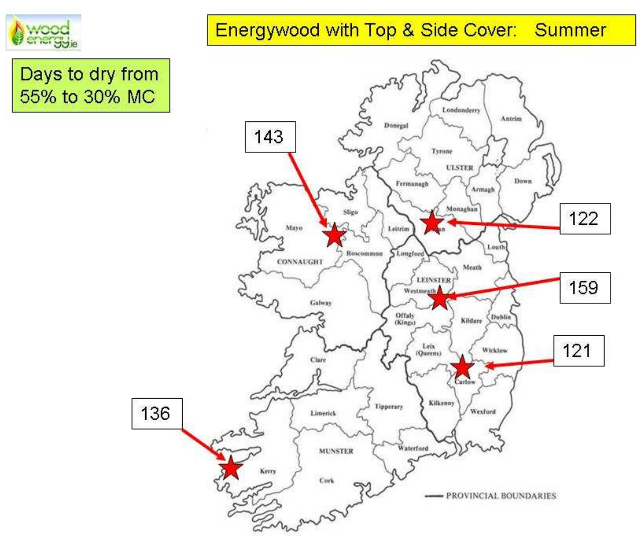


Figure 2. Predicted number of days for Sitka spruce energywood to dry from 55% to 30% moisture content at various locations within Ireland when initial drying began at the beginning of summer. Differences are due to precipitation and evapotranspiration.

The second drying trial confirmed that uncovered material dried at slower rates (-8 to -33%) than covered material. It also showed that there were differences between species; covered lodgepole pine dried slightly faster than Sitka spruce (+8%) and considerably faster than Eucalyptus nitens (+87%).

The data collected on Douglas-fir and hybrid poplar moisture contents in Oregon allowed the development of drying curves (e.g. Figure 3.) and climate based air-drying models. Oregon can be divided into nine climate zones. Similar to the work completed in Ireland, the models allowed extension of the results to other climate zones than those in which the data was gathered.

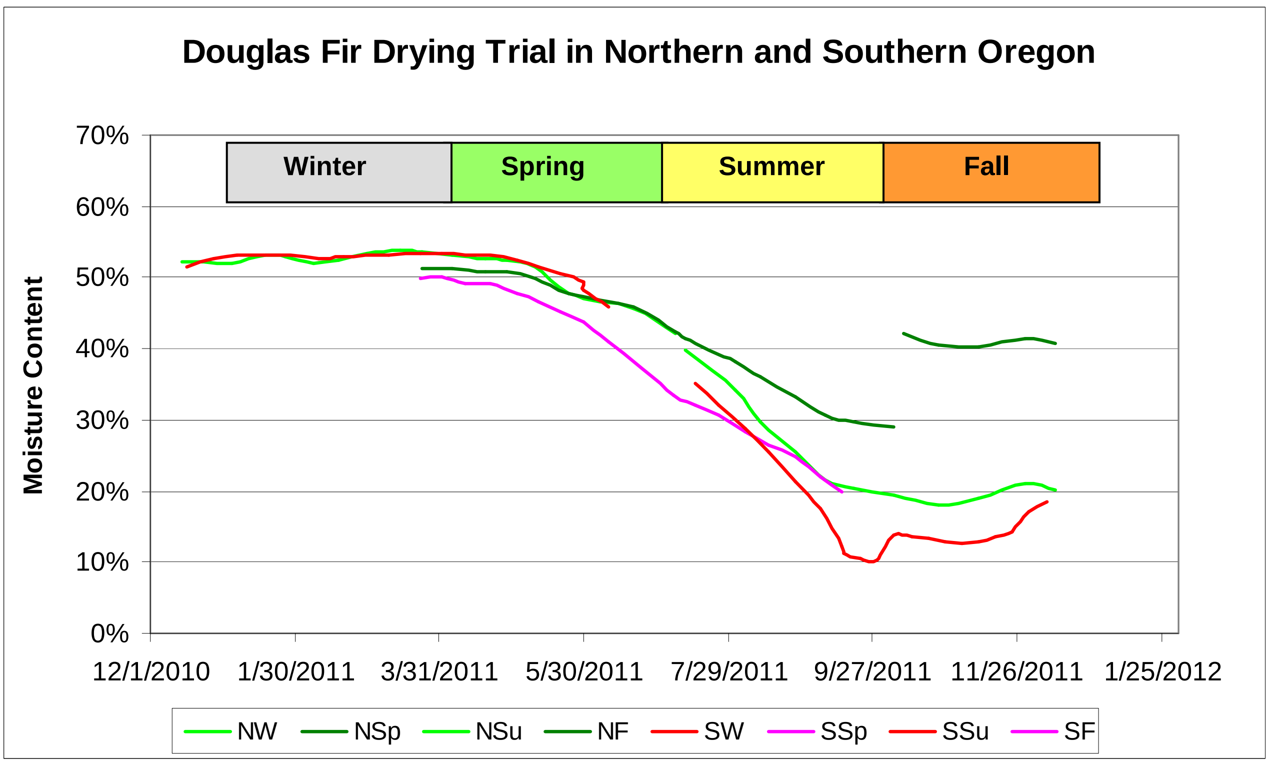


Figure 3. Drying curves for Douglas-fir smallwood log bundles in northern and southern Oregon.

Considerable differences were noted in drying rates between:

- climate zones (not unexpectedly, in dryer zones wood dries faster than in wetter zones)
- season in which drying began (spring or summer are better seasons to begin drying than fall or winter)

- material size (smaller poplar logs dry faster than larger poplar logs), and
- species (poplar logs dry faster than Douglas-fir logs of the same size).

As an indication of the variability in forecast drying rates, there was a range of 507 days between the lowest and highest number of days required to dry woody material down to 30% moisture content.

Evaluation of Monitoring Tools

Virtually all of the tools evaluated required some form of calibration to improve the accuracy of moisture content measurements. The Humimeter BLW used on Sitka Spruce roundwood in Ireland was the exception. This same tool, however, required calibration for all of the species evaluated in Oregon. Calibration models between actual and measured moisture content (or acoustic velocity in the case of the acoustic tools) generally explained less than 80% of the variability in measurements.

In both Ireland and Oregon, the Humimeter BLW tool proved to be the better of the two conductance tools evaluated for roundwood moisture content measurement from accuracy and precision perspectives. However, when an attempt was made in Oregon to validate the calibration model with a data set gathered four months later the Humimeter BLW gave unacceptable correlations between calibration adjusted measurements and actual moisture content measurements (R^2 = 0.09). On the other hand, this tool did give acceptable moisture content measurements in Ireland, particularly at lower moisture content levels (Figure 4).

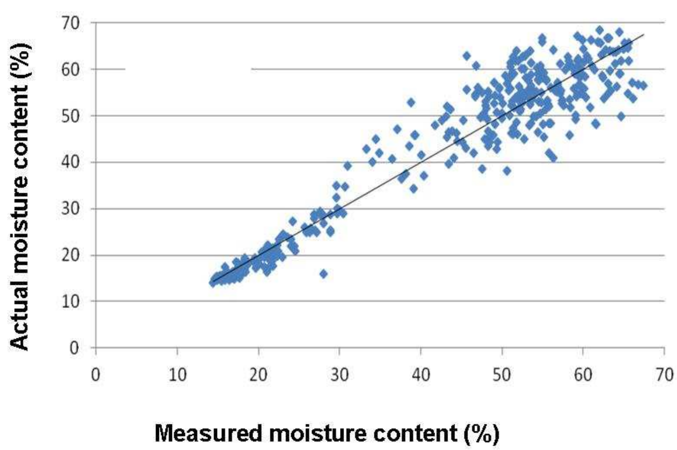


Figure 4. Actual versus measured moisture content using the Humimeter BLW on Sitka spruce roundwood logs in Ireland.

The Fiber-Gen HM200 proved to be the best of the two acoustic tools evaluated for measuring moisture content of roundwood logs (R^2 = 0.82 for the calibration model and 0.78 for the validation model when tested with Douglas-fir). The calibration model indicated that a number of species (western hemlock, Douglas-fir, ponderosa pine, and madrone) had similar calibration coefficients, while other species (oak and poplar) required individual species calibration coefficients.

Neither of the capacitance tools performed well when measuring moisture content of slash bundles in Ireland. Both tools required calibration, but the best calibration model still accounted for less than 36% of the variability in measurements. The Wile Bio Meter performed slightly better than the GE Balemaster in slash bundles.

Tests in Ireland of the four capacitance tools for measuring lodgepole pine wood chip moisture contents showed that all of the tools required calibration and different tools performed better within given moisture content ranges than others (Figure 5). At moisture contents above 40% all tools would significantly underestimate moisture content without calibration. Accuracy of the tools was slightly better at moisture contents below 40%. Variability in measurements was greatest for the Wile Bio Meter and GE Timbermaster tools and least for the Humimeter BM and Humimeter BLL tools over all moisture contents.

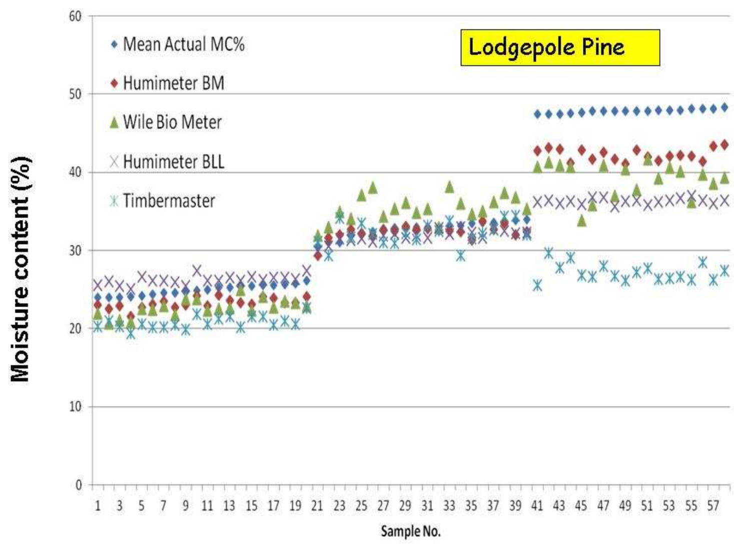


Figure 5. Performance of four capacitance tools for measuring moisture contents in lodgepole pine wood chips.

Tests in Oregon of the two capacitance tools for measuring wood chip moisture contents showed that both tools required calibration. Neither tool performed well at moisture contents below 30%. Above 30% the Wile Bio Meter performed slightly better (R^2 = 0.82) than the Humimeter BM1 (R^2 = 0.79). The calibration model for the Wile Bio Meter indicated that a number of species (western hemlock, Douglas-fir, and madrone) had similar calibration coefficients, while other species (ponderosa pine, oak and poplar) required individual species calibration coefficients. Similarly, the calibration model for the Humimeter BM1 indicated that a number of species (western hemlock, madrone, oak and poplar) had similar calibration coefficients, while other species (ponderosa pine and Douglas-fir) required individual species calibration coefficients.

The two capacitance tools tested in wood chips in Oregon were also tested in hogfuel (chipped limbs and tops). Results were similar to those for wood chips, except that performance tended to be worse for both tools (R^2 between 0.62 and 0.76) and species groupings for calibration purposes were slightly different.

There are some similarities and differences between these results and those obtained by Jensen et al. (2006). Jensen et al. (2006) evaluated one NIR reflectance, five capacitance, zero acoustic, and zero conductance moisture meters to test their capability of measuring moisture content on solid biofuels. Results obtained showed that the most promising calibrations were acquired with an NIR reflector (Mesa MM710, R^2 = 0.84-0.99) and two of the capacitance moisture meters (Pandis FMG 3000, R^2 = 0.89-0.99 and Schaller FS 2002-H, R^2 = 0.86-0.96). The Wile Bio Meter did not rate in the top three meters evaluated by Jensen et al. (2006). In our study the Wile Bio Meter capacitance tool (R^2 = 0.92) and the Fiber-Gen Hm200 acoustic tool (R^2 = 0.78) were the most effective tools. The calibration equations developed by Jensen et al. (2006) indicate that both laboratory and fuel type affect measured moisture content. Differences between our results and their results could be due to the effect of the operator (i.e., level of experience with a given tool), number of samples used, methods used, data analysis methods, and the species and fuel types evaluated.

Of the eight tools evaluated, three exhibited mechanical reliability problems within the test periods; problems occurred with the Humimeter BM after about 100 readings, with the Humimeter BLW after about 400 readings, and with the Humimeter BLL after about 1000 readings. No mechanical reliability problems were found with the other tools evaluated.

The best two in each tool category was determined on the basis of tool efficiency (Figure 6). Tool efficiency was determined from the time per sample measurement multiplied by the sample size needed to be within 3% of the true mean value. Variance in the sample size calculations was based on the combined data from all six species measured. The Wile Bio Meter was the most efficient capacitance tool in chips or hogfuel. The Humimeter BLW was the most efficient conductance tool in roundwood logs. The Fiber-Gen HM200 was the most efficient acoustic tool in roundwood logs. Follow on tests indicated that sample size could be reduced and tool efficiency improved when working with a single species.

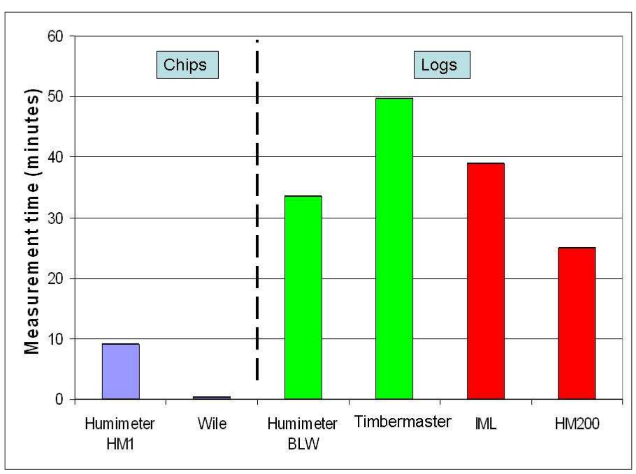


Figure 6. Tool efficiency (time required to obtain mean sample measurements within +/- 3% of the true mean moisture content.

PRELIMINARY CONCLUSIONS

Software tools have been developed which allow quantification of the economic effects of moisture content in forest to buyer supply chains. These show the importance of managing moisture and can be used to evaluate different moisture management approaches.

Drying trials and the climate based air-drying models that have been developed based on these, allow forecasting of time to dry in various locations around Ireland and Oregon. They also allow determination of the effects of different harvesting seasons, different storage methods (covered or uncovered), and different species on drying time.

Although there are a range of different tools and technologies available for in-situ measurement of moisture content most tools require calibration for species and material type. Even then, these tools are not particularly precise. For some tools mechanical reliability has been identified as an issue. Considerable range in measurement efficiency was identified between tools. Further work is required on tool selection and development of sampling protocols is needed.

LITERATURE CITED

Energy Information Administration. 2010. International Energy Outlook: Energy Information
Administration: Washington, D.C.: http://www.eia.gov/oiaf/archive/aeo10/index.html (accessed 19 July 2012).

Fauchon T., Deleuze C., and Chantre G. 2006. How to control the variation of the wood moisture content of logs from the stand to the woodyard? The contribution of both direct techniques of assessment and modeling. AFOCEL. Laboratorie Bois Process (Wood Processing Lab). France.

Jensen, P.D., Hartmann, H., Bohm, T., Temmerman, M., Rabier, F., and Morsing, M. 2006. Moisture content determination in solid biofuels by dielectric and NIR reflection methods. Biomass and Bioenergy 30: 935-943.

Jirjis, R. 1995. Storage and drying of wood fuel. Biomass and Bioenergy. 9(1-5): 181-190.

Real-time Monitoring mass-Flow of Woodchips bases on Force Sensor

Pengmin Pan[1], Timothy McDonald[2], Steve Taylor[3] and John Fulton[4]

Abstract

To measure the woodchip mass for truckload weights and show mass flow rate real time, a dynamic force transducer was used to collected woodchip data at sampling frequency of 10kHz. Force response was correlated with mass flow using a model based on a principle components regression (PCR). The principal components were generated from power spectral densities (PSD) calculated using Welch method. Since diameters of stems at breast height (DBH) have high correlation with woodchip mass ($R^2 > 0.9$), predicted mass flow was compared to measured DBH. Results showed significant correlation between predicted diameters based on the PSD/PCs model and measured DBH ($R^2 = 0.81$). The approach seems feasible for measuring mass flow in real time.

Keywords: woodchip, mass-flow, power spectral densities, diameter

Introduction

Auburn University is among a group of research organizations investigating efficient harvesting and logistical systems for procuring small-diameter woody biomass for energy. The goal of the DOE-funded project is to develop state-of-the-art, low-cost systems to provide high quality feedstock for conversion to liquid fuels.

An important aspect of the project has been to develop technological solutions to solve problems limiting productivity or impeding quality assurance in the procurement process. Variation in moisture content has been identified as a potential problem in sourcing biomass for a conversion facility, particularly if in-field drying is used to increase transport efficiency. Some biomass-consuming mills, particularly those using thermochemical processes, would prefer to pay for raw material on an energy basis, rather than wet weight, to favor those suppliers bringing the driest wood. Practical moisture sensing systems on both ends of the procurement chain were felt to be an essential element in such a payment scheme in order to foster trust between suppliers and consumers. As a step towards this end, we have begun development of such a moisture content measurement

---

[1] Graduate Research Assistant. Biosystems Engineering Department. Auburn University.

[2] Associate Professor Biosystems Engineering Department. Auburn University.

[3] Professor and Head. Biosystems Engineering Department. Auburn University

[4] Associate Professor. Biosystems Engineering Department. Auburn University

system for use on a chipper to sense water content of chips as they are blown into a van.

An essential precursor to such a system is the ability to measure mass flow rate of chips as they exit the chipper chute. We developed and tested such a device for this project, one that was practical, fairly simple, inexpensive, and relatively robust. This report will provide details of the design along with some preliminary testing results.

Materials and methods

Mass flow sensors are common on agricultural combines for a variety of applications. Many use an impact method of sensing flow rate (*Birrell and others, 1996*). In this approach, the stream of material is directed onto a force transducer that senses a change in momentum as it impacts a plate. The resulting force is used to predict mass flow. A similar approach has been used in the chipper mass flow system. A hinged element was added to the end of a chipper (*Precision Husky Corporation*[5] *model 3084 WTC*) chute as Figure 1. A fixture mounted between the fixed and movable portions of the chute held a dynamic mass flow sensor (*Omega Engineering, INC model DLC101-50*) that was loaded in compression when chips impacted the hinged plate. The output from the sensor was a voltage signal proportional to force and was read using a National Instruments USB-6210 data acquisition module. The data were sampled at 10 kHz and recorded using a program written in Labview2010 (*National Instruments Corporation*).

Figure 1. Force response measuring

[5] The use of trade names is for information purposes only and does not apply any endorsement by Auburn University.

No independent measure of wood chip mass flow was found to be practically feasible, so experiments were instead conducted to correlate sensor output with tree DBH. Data collected by partners in the study consortium indicated DBH and weight were highly correlated for the types of stands being harvested, specifically, relatively young loblolly pine plantations. Figure 2 is a plot of the relationship between weight and DBH for a range of typical tree sizes found in the stands. A linear regression of DBH on weight was found to be significant ($P < 0.001$) with R-square in excess of 0.9.

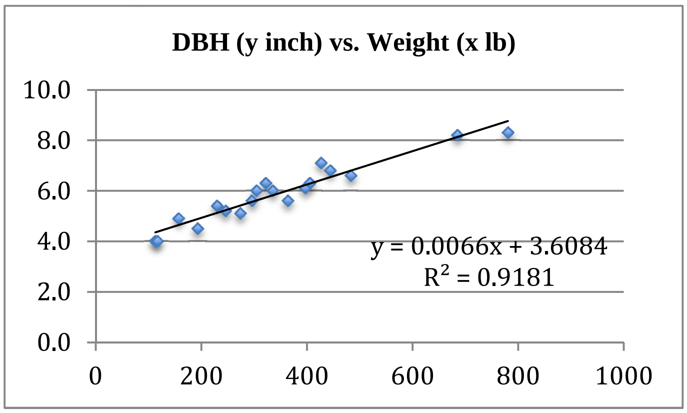


Figure 2. Regression result between DBH and weight

Experiments consisted of measuring sensor output over the entire duration of a single tree being chipped. The time period used (33 seconds) was fixed. Figure 3 shows a plot of the typical force response while chipping a single stem. The 33-s duration was sufficient, in most cases, to record force while the entire stem was chipped. Problems with sampling the entire tree were sometimes encountered when, for example, the stem became hung in the debarker prior to entering the chipper. Stems in groups of about 10 were laid out on the logging deck near the chipper and measured for DBH and total height. Stems were then fed individually into the debarker and the chipper. Force response was measured and stored for each stem. Valid data for a total of 98 stems were measured sampling in this manner.

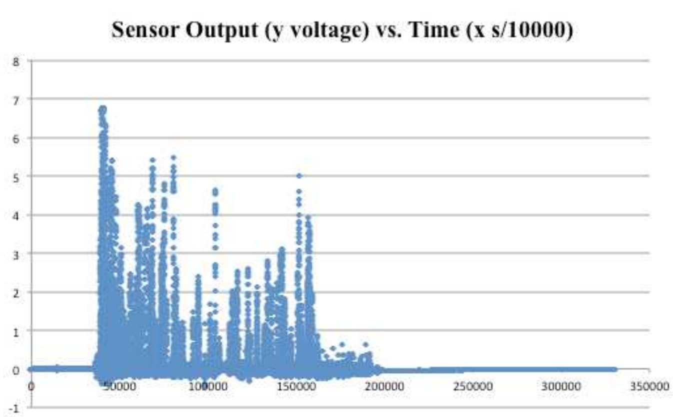


Figure 3. Force response example during chipping

Two types of measures were calculated on each force record for correlation with tree DBH. These measures consisted of the following:

a) Response sum. This was simply a sum of all force observations from beginning to end of the sampling period.
b) Power spectral density (PSD). The power spectrum of a signal describes the power per unit frequency it carries. PSD were calculated for each force response in Matlab2010a (*The MathWorks, Inc.*) using the Welch method with Hanning windows at length of 4096. This resulted in a relative power value at numerous (4096) discrete frequencies, only some of which were assumed related to size of the tree.

A principle components analysis (PCA) was used to determine smaller groups of frequencies most closely correlated with tree size. The ten principal components most highly correlated with DBH were then selected and used in a stepwise regression analysis to determine the smallest set of values most closely predicting tree size. A random selection of eight force records was reserved and the prediction model built from the remaining 90 observations. Finally, predictions for the eight reserved trees based on the completed model were compared to actual DBH measurements.

Results and Discussion

There was no correlation observed between the summed force response and tree DBH. Figure 4a shows a graph of DBH versus force sum for the 90 observations. It was surprising how completely unrelated the two were. We had originally thought a larger tree would produce a bigger force over the same length of time since the chipper fed at a constant rate and the trees were about the same height regardless of diameter. The sum should, therefore, have been greater for a larger tree, but this was not the case.

The PSD approach, however, proved more effective at capturing diameter information. The stepwise regression process resulted in a model having five total independent variables, four of which had p-values < 0.002, the fifth with $p < 0.1$. Using these variables, the relationship between predicted and actual DBH was as seen in Figure 4b. The R-square value in this case was 0.69. This result perhaps indicated that, although the chips were striking the impact plate as they exited the chute, their path was not changed a great deal and, therefore, force measurements were relatively low. This was intentional in that we did not want to alter the flow of chips into the van and cause problems filling its volume. Though the magnitude of the impact force of chips was not altogether different for larger trees, the rate at which they struck the plate seemed to be changed and this put higher frequency variations into the force signal. These higher frequency components were more pronounced for larger trees, indicating a more rapid rate of chip impact, and this was detected in the spectral analysis of the signal.

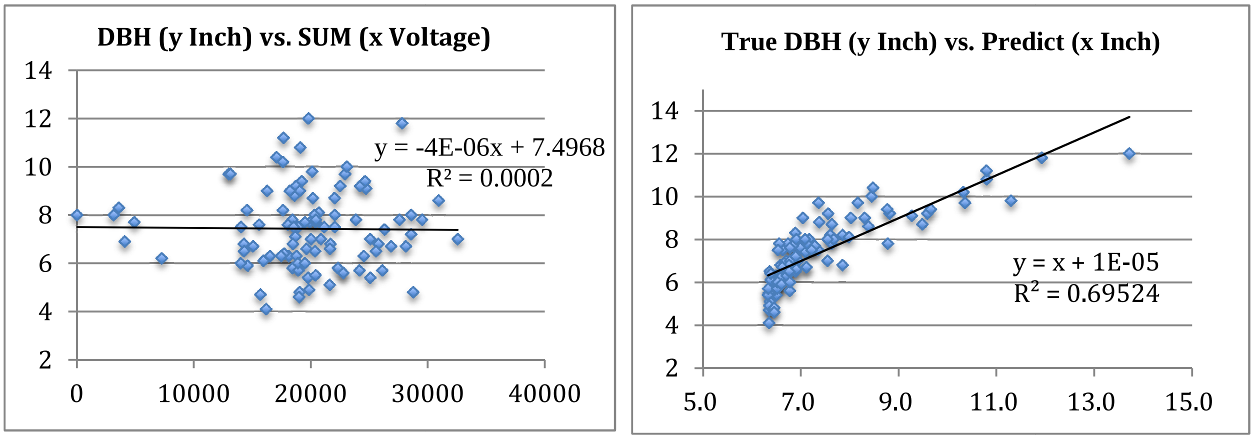


Figure 4. Regression model for direct sum and PSD

The model was used to estimate DBH for the eight reserved trees and results were summarized in Table 1 (marked as Lin for linear). For trees larger than about 6 inches DBH, the size estimates were typically within 10% of the actual value. For smaller trees, however, the prediction was inaccurate, with size being overestimated. The poor results for smaller trees could have been the result of background noise. Impact forces were relatively small for even large trees and shaking of the chute could easily have overwhelmed the response for smaller stems. This effect was visible in the results shown in Figure 4b mainly as a significant nonlinearity at low DBH. A log-transformation was applied to the regression data in an attempt to counteract the nonlinearity at low DBH. The regression of predicted to actual DBH for the transformed data are shown in Figure 5. A good linear relationship between true DBH and predicted value was obtained with higher R-square. The eight reserved trees were also tested using the log-transformed model and results were listed in Table 1 (marked as Log). Clearly the log-transformation method improved the prediction accuracy significantly for small DBH trees, average error decreasing from 7.90% to 5.77%. Interestingly, the prediction accuracy for larger trees seemed to go down slightly.

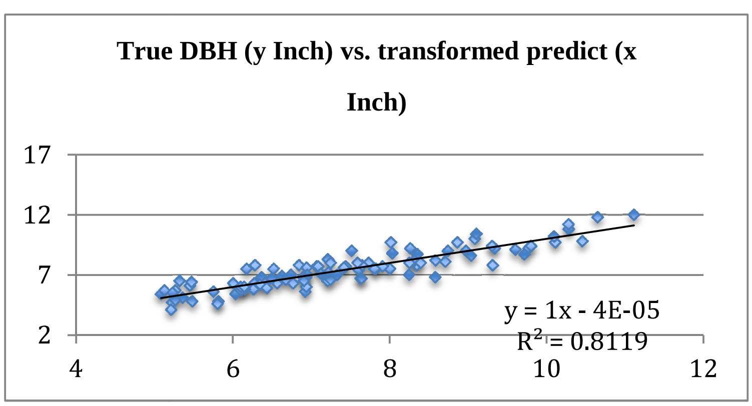


Figure 5. Regression model for log-transformed data

Table 1. True stem diameter vs. predicted value for PC regression

TREE NO.		1	2	3	4	5	6	7	8	Average
Predicted	Lin	12.3	6.9	10.9	7.8	6.2	7.0	6.5	7.3	8.11
	Log	10.7	7.3	10.3	8.5	5.2	7.6	6.2	7.8	7.95
True DBH		11.8	7.0	10.8	8.2	4.7	7.4	5.8	7.5	7.9
Error **Absolute value**	Lin	4.15%	0.99%	1.05%	4.53%	31.91%	5.64%	12.55%	2.35%	7.90%
	Log	9.32%	4.29%	4.63%	3.66%	10.64%	2.70%	6.90%	4.00%	5.77%

An experiment was conducted to test if these results calculated for individual trees might be applicable in a production situation in which multiple stems were moving through the chipper on a continuous basis. Fundamental to this analysis was the assumption that the same force response would be seen whether a single stem, or multiple stems, were being chipped as long as the total cross-sectional area were the same. The difference in the two scenarios was the lack of knowledge about when a stem might begin or end its trip through the chipper. In our original tests, data were captured while the entire tree was chipped. In a production setting, the beginning and ending points would vary for each of many stems going through at any one time and it would not be possible to calculate the PSD and subsequent prediction based on the entire, individual-stem force signal. It was felt a discontinuous sampling strategy would be most practical in this scenario, that is, making estimates of mass flow over short bursts of time and accumulating them to predict total mass flow.

Four different sampling strategies were evaluated in these experiments. For each one, the sampling process was applied to the continuous data collected for individual stems, and the resulting DBH calculated using the PC regression model for the (shorter) periods of time covered. All these DBH estimates were then averaged and compared to the global average DBH for all stems. The four sampling strategies were as follows.

1. Continuous sampling over short periods
   a. Two second intervals
   b. Five second intervals
2. Discontinuous sampling
   a. Sampling every other second
   b. Sampling two seconds, then waiting three seconds

Results are found in Table 2. For continuous sampling (strategies 1a. and 1b. above), all data were contained in the PSD computation and, as might be expected, the global DBH estimate was closer to the true value, differing by less than about 0.3%. For the partial sampling strategies (2a. and 2b. above), there was some loss in accuracy with global DBH estimates differing by about 1.8%, or less, from the true value. The correct approach to use in creating a production mass flow sensor would be related to the practicalities involved in developing the system itself. If the PSD calculations could be done in real time, the continuous strategy would most likely be more accurate in predicting DBH. If it were necessary to store data in order to make the PSD calculation, then the discontinuous approach would perhaps be more suitable with only a slight decrease in total accuracy.

Table 2. DBH calculation from different sampling methods

Sampling Methods	**Prediction DBH on Average (inches)**	**True DBH (inches)**
Two second intervals	7.41	7.43
Five second intervals	7.42	
Sampling every other second	7.36	
Sampling 2s then waiting 3s	7.30	

Conclusion

An approach to measure mass flow rate of chips exiting a chipper was presented. The method used a force measurement over time to estimate mass flow. Data were correlated to tree size (and therefore weight) using a prediction model based on the force signal power spectrum. Results showed good agreement between measured and predicted individual tree DBH for the conditions used in these tests. Other experiments indicated the approach would be applicable for continuous measurement of mass flow from multiple stems, but this was not verified in practice. Further research will test the method for multiple stems and verify accuracy of predicted truckload weights.

Literature Cited

Birrell, S. J., K. A. Sudduth, and S. C. Borgelt. 1996. Comparison of sensors and techniques for crop yield mapping. *Computers and Electronics in Agriculture* 14(2-3): 215-233.

Acknowledgements

The authors wish to thank Doc Flynn for his assistance in making the chute modifications and Troy Braden of Corley Land Services for facilitating the tests. Thanks to John Klepac of the US Forest Service for providing tree size and weight data. We would also like to gratefully acknowledge the support of the Department of Energy in providing funding for the work.

Trucking Characteristics for an In-woods Biomass Chipping Operation

Jason D. Thompson, John Klepac, Wesley Sprinkle
USDA Forest Service

Abstract

A study was implemented to evaluate the transportation of woody biomass. This paper reports on the results of transporting wood chips produced in the field from transpirationally dried trees. For the study, a stand of timber was felled and allowed to dry in the field for approximately six weeks. The timber was then chipped in the woods and transported to market. In order to maximize payload of the dry chips, larger capacity trailers were utilized along with the contractors existing chip trailers. The larger trailers (123 yd^3) contain 19% more volume than the traditional trailer (100 yd^3), but only increased payload by 10%. Additionally, the extra payload was still 16% below the legally allowed payload.

Introduction

Efficient transportation is a critical component to insure a viable woody biomass industry. New material specifications and transportation options ranging from dry chips and microchips to larger capacity trailers present more challenges and options to producers. A study was implemented to look at the various components of transporting woody biomass in order to identify bottlenecks in the system and potential solutions. The overall study will examine the dynamic between company owned and contract trucks, cycle time analysis for all transportation components and product classification and analysis. The contractor produces a variety of products, ranging from traditional clean and whole tree green chips/microchips to clean and whole-tree dry chips/microchips. Through the course of the study each transport system will be fully described including volumetric payload capacity, weight-limited payload configurations, trailer costs, tractor fuel consumption, and hourly owning and operating costs. In addition, time study and trip monitoring will be used to document a sample of transport cycles to measure travel time (speed) on different classes of typical southern roads, loading and unloading time, and the occurrence of delays and interruptions. This paper reports on the results of one aspect of the overall project, the transportation of transpirationally dried wood chips.

Study Background

As part of a larger woody biomass study, an approximately 30 acre stand of loblolly pine plantation in southeast Alabama was felled and bunched. The trees were left to dry in place for approximately six weeks. The trees were then skidded and chipped on site with a mobile disc chipper. The chips were blown into the trailers. An additional 7 acres of green trees from the stand were felled, skidded and processed following the chipping of the transpirationally dried trees. The goal of the study was to evaluate the potential moisture loss of the trees, and cost and productivity of the processing and transportation operations for drier chips. The green trees were harvested as a comparison and to represent industry standards of harvesting and processing green trees.

Results and Discussion

In anticipation of transporting drier (lighter) chips, larger capacity chip trailers were added to the trucking fleet. The larger trailers were 123 yd^3 (large), while the existing trailers were 100 yd^3 (regular) and 88 yd^3 (small). The goal of using the larger trailers was to maintain as close to a legal payload as possible with the drier chips.

Drier chips potentially have a higher value to end users due to the higher net energy content (BTU) gained by removing moisture. Moisture content was calculated for green and dried trees during the study. It was found that green trees had an average moisture content of 54% and the dried trees had an average moisture content of 39%, resulting in an average weight loss was 15%.

The load tickets for the tract were used to analyze load data. A total of 1393 tons (61 loads) were processed from the transpirationally dried trees. Table 1 shows the results of the load analysis. The large trailers were used to transport 934 tons on 39 loads. The regular and small trailers were used to transport 344 tons (16 loads) and 115 tons (6 loads), respectively. The Large trailers averaged a net payload of 23.96 tons, while the regular and small trailers averaged 21.51 tons and 19.24 tons, respectively. The maximum legal load, using a tare weight of 15.5 tons, was calculated at 28.5 tons. With an average of 23.96 tons/load the large trailers were 16% below the legal payload and the regular and small trailers were 24.5% and 32.5% below the legal limit, respectively. These figures represent a large increase in transportation cost due to lost payload capacity.

Table 1: Truck load data for transpirationally dried wood chips.

	Large-Dry	Regular-Dry	Small-Dry
Capacity (yd^3)	123	100	88
# Loads	39	16	6
Avg. Wt. (tons)	23.96	21.51	19.24
Min Wt. (tons)	20.67	20.11	17.72
Max Wt. (tons)	29.03	22.83	20.78
Avg. Tare Wt. (tons)	15.38	15.24	15.01
Avg. Density (lbs/ft^3)	14.42	16.00	16.23

A bulk density for each load was calculated by dividing the net weight of the load by the volume of the trailer. The void formed at the back of the trailer from the chips sloping down to the trailer gate was subtracted from the trailer volume. Otherwise, it was assumed the trailer was completely full. The calculated load density for the large trailer was the lowest of the three at 14.42 lbs/ft^3, which is 10% less than the density of the regular trailer. The regular trailer and small trailers averaged 16 and 16.23 lbs/ft^3, respectively. A paired t-test procedure was used to test for significant differences between the calculated load densities. It was found that the large load density was significantly (<.0001) different than the regular load density. The t-test also indicated that there was no significant difference (<.0001) between the densities of the regular and small trailer densities. These results indicate that a physical characteristic of the large trailer, chips, loading method or a combination of these is affecting load density. Possible reasons are that the large trailer is too long and the chips are to light and cannot be blown far enough. To achieve the legal payload with the large trailer would have required a load density of 17 lbs/ft^3. This exceeds the density achieved with the smaller two trailers and suggests that it is not feasible as the system is configured now. A net load of 26.6 tons could be realized if the load density of the large trailer could be increased to that of the regular trailer (16 lbs/ft^3). At a density of 14.42 lbs/ft^3 a trailer with a capacity of 146 yd^3 would be required to reach maximum payload.

The green chips transported from the tract were also analyzed (Table 2). On-board scales were not installed on any of the truck/trailer combinations used on the study. The large trailers were not filled to capacity in order to avoid surpassing the legal limit (44 tons gross). Therefore, this data is presented but is not included in the overall analysis of the results. The data from the regular and small trailers represent fully loaded trailers.

Table 2: Truck load data for green wood chips.

	Large-Green	Regular-Green	Small-Green
Capacity (yd^3)	123	100	88
# Loads	7	7	3
Avg. Wt. (tons)	24.94	25.81	25.20
Min Wt. (tons)	21.6	23.1	24.13
Max Wt. (tons)	28.46	28.47	26.3
Avg. Tare Wt. (tons)	15.49	15.16	14.13
Avg. Density (lbs/ft^3)	15.00	19.20	21.26

A total of 429 tons were produced from the green trees during the study. The regular trailers were used to transport 180 tons on 7 loads and the small trailers transported 75 tons on 3 loads. The resulting average load density was 19.2 lbs/ft^3 and 21.3 lbs/ft^3, for the regular and small trailers, respectively. A paired t-test was performed to determine if the density of the green loads (19.2 lbs/ft^3) was different than that for the dry loads (16.00 lbs/ft^3) on the regular trailer. The results showed that there was a significant difference (<.0001) between the densities. This result is expected considering the 15% weight difference between the green and dry chips. The results from a paired t-test procedure between the load densities of the regular and small trailers were found to be significant (0.047). Due to the low number of observations for the small trailer (n=3), no firm conclusions can be drawn from this result.

Conclusions

The use of larger trailers to haul transpirationally dried chips increased payload 10% over the regular chip trailers used by the contractor. The number of loads required to transport all chips from the site could have been reduced by 6 if the larger trailers had been used exclusively. This gain, however, was still 16% below the maximum legal load.

There was a significant difference between the bulk densities of the large trailer and the regular trailer when hauling dry chips. Although all trailers appeared to be completely full before departing, this cannot be confirmed. The lower density suggests that a characteristic of the trailer or a material property of dry chips is contributing to the reduced load density. The large trailer may be to long for the lighter chips to be blown and packed into the front of the trailer. This would indicate that a different trailer configuration or loading method might be required to achieve maximum density. Possible solutions include low profile tires that would allow for an increase in trailer height or top loading the trailers. The number of loads could have been further reduced by 12 if the large trailers could be loaded at a density of 16 lbs/ft^3. This equates to an increase in load size of 19% over the regular trailers.

Future Work

In order to determine the reasons for the lower load density measured in the large trailers additional work needs to be performed. This may involve modifying the trailers with view ports or adding instrumentation to allow observations of chip levels within the trailer. Additionally, alternative trailer configurations or loading methods might be evaluated. Work is presently under way to evaluate the logistics of transporting transpirationally dried long wood as an alternative to chips.

Acknowledgements

This work was partially funded by the Department of Energy under agreement 10-CO-11330132-088. The authors would also like to thank Corley Land Services and Auburn University for their cooperation with this project.

Skid trail stream crossing closure BMPs affect stream sedimentation

Laura R. Wear[1], W. Mike Aust[2], M. Chad Bolding[3], Brian D. Strahm[4] and C. Andrew Dolloff[5]

Abstract

Sediment is the most widespread water pollutant in the United States. In silvicultural operations, roads, decks, and skid trails having bare soil are most likely to contribute to erosion and sedimentation. Forestry best management practices (BMPs), when considered as an aggregation, are often effective at reducing the transport of soil into nearby streams. However, stream crossings for roads and skid trails are most often where sediment is deposited directly into streams, even when BMPs are implemented. Stream crossings can serve as direct conduits for eroded soils to enter streams and stream crossings circumvent streamside management zones. Thus, BMPs for stream crossings are critical to protect water quality. However, the efficacies of specific BMPs on water quality are a current research gap. In this study, located in the Piedmont of Virginia, three post-harvest skid trail stream crossing approach BMP treatments on the same stream were monitored to determine their efficacy in reducing sedimentation: slash, mulch, and mulch plus silt fence. Upstream and downstream water samples (from stream crossings) were collected daily for 10 months following timber harvesting. Samples were evaluated for total suspended solids (TSS). Results indicate that mulch is the most effective treatment in preventing sediment from entering the stream at the stream crossing approach (the highest sediment inputs were 0.34 tonnes per day during peak rain events). Slash was also an effective BMP (maximum sediment input was 0.79 tonnes per day), however the use of silt fence directly adjacent to a stream bank was more detrimental than beneficial for water quality. During peak rain events, median sediment loading at the mulch + silt fence crossing reached 1.02 tonnes per day, five times more than the mulch treatment.

Introduction

Sediment is considered the pollutant that is most widespread in our nation's waters (US Environmental Protection Agency 2003). Sedimentation in streams often increases following land use activities including urbanization, agriculture, silviculture, and mining (Marcus and Kearney 1991). Although silviculture generally results in less non-point source pollution (NPSP) than other land uses, forest roads and skid trails have been clearly identified as the component of forest operations having the greatest potential to

[1] Former Graduate Research Assistant, Virginia Tech, Department of Forest Resources and Environmental Conservation
[2] Professor, Virginia Tech, Department of Forest Resources and Environmental Conservation
[3] Associate Professor, Virginia Tech, Department of Forest Resources and Environmental Conservation
[4] Assistant Professor, Virginia Tech, Department of Forest Resources and Environmental Conservation, 228 Cheatham Hall, Blacksburg, VA, 24060.
[5] Project Leader, USFS Southern Research Station Coldwater Fisheries Research Unit, 1710 Research Center Drive, Blacksburg, VA 24060.

introduce sediment into streams (Patric 1976, Rothwell 1983, Arthur et al. 1998, Swift and Burns 1999, Aust and Blinn 2004, Grace, 2005). Sediment from forest roads can impair surface water physically, biologically, and ecologically (Great Lakes Environmental Center 2008). High levels of sediment may cause permanent alterations in community structure, diversity, density, biomass, growth, and rates of reproduction and mortality in aquatic organisms (Henley et al. 2000). The stream crossing portion of the forest road is where sedimentation occurs most because of the direct intersection of the road and the stream (Rothwell 1983, Grace 2005). It has been found that sediment values are typically greater downstream of a stream crossing, compared to upstream values (Rothwell 1983, Lane and Sheridan 2002). Skid trails may have more potential for erosion than haul roads because they are built to lower standards than haul roads (Grushecky et al. 2009), usually without water control structures.

Forestry best management practices (BMPs) are employed in over 40 of the United States (Archey 2004) and are generally effective at reducing erosion and sedimentation (Arthur et al. 1998). Although BMP implementation rates are greater than 85% in the eastern US (Ice et al. 2010), more research is needed regarding the effectiveness of specific forestry BMPs in order to maximize their efficiency (Anderson and Lockaby 2011). Clinton and Vose (2003) highlighted recent attention paid to the impacts of forest roads on stream health. They noted the pressures placed on land managers, organizations, and regulatory personnel to protect both terrestrial and aquatic systems that might be negatively affected by forest management operations. Additional information regarding forest operations, BMPs, and water quality impacts are needed to assist these managers in their decision making process. The objective of this paper is to evaluate three levels of skid trail stream crossing closure techniques (slash, mulch, and mulch + silt fence) on stream sediment levels, in order to provide land managers, landowners, and loggers with options for erosion control at stream crossings. Research questions include: 1) Will the three stream approach closure treatments result in different levels of sediment loading downstream of each crossing?, and 2) Will the closure treatments result in different total costs?

Materials and Methods

Study Site

Three stream crossings were located on an operational timber tract in the Piedmont physiographic region of Virginia (Buckingham county) (Figure 1). The site selected had three temporary stream crossings on the same stream, and used portable metal bridges for skidder stream crossings (Figure 2). This paper is a sub-study within a larger research project (Wear 2012). The benefit of having the crossings located on the same stream is to control for different in-stream and watershed-specific variables. The stream was intermittent, with continuous flow for 10 months during the study. Further stream crossing characteristics are provided in Table 1.

The site was located on MWV property and was harvested in the fall of 2010. The 25 year old stand was managed loblolly pine (*Pinus taeda*). A clear-cut harvest was conducted with rubber-tired feller bunchers and grapple skidders. Total harvest area was 54 ha. Skidder stream crossings were located prior to harvest by a professional forester in order to minimize the number of crossings needed to access the timber. The steel paneled skidder bridges varied from 7.3 to 9.7 meters in length. Three panels (1 m wide) were used on each crossing. Panels were installed and removed with rubber tired grapple skidders, thus some stream bank disturbance occurred. A 15 m streamside management zone (SMZ) was intended for each side of the streams, but ranged from 13-20 m.

The study site had a mean annual precipitation of 114 cm (45 in) per year, and a mean annual air temperature of 12℃ (55℉) (USDA Natural Resources Conservation Service 2011). Topography was rolling with average sideslopes of 15% and maximum sideslopes of 25%. Soils were fine, mixed, semiactive, mesic Typic Hapludults (USDA Natural Resources Conservation Service 2011). The sites were typical old farming fields that had reverted to eroded forestland as is typical of the Piedmont region (Nutter and Douglass 1978). Excessive erosion, evidenced by numerous gullies, had occurred on the site. Sediment originating from the past disturbance is still present in many Piedmont streams such as these (Nutter and Douglass 1978, Jackson et al. 2005).

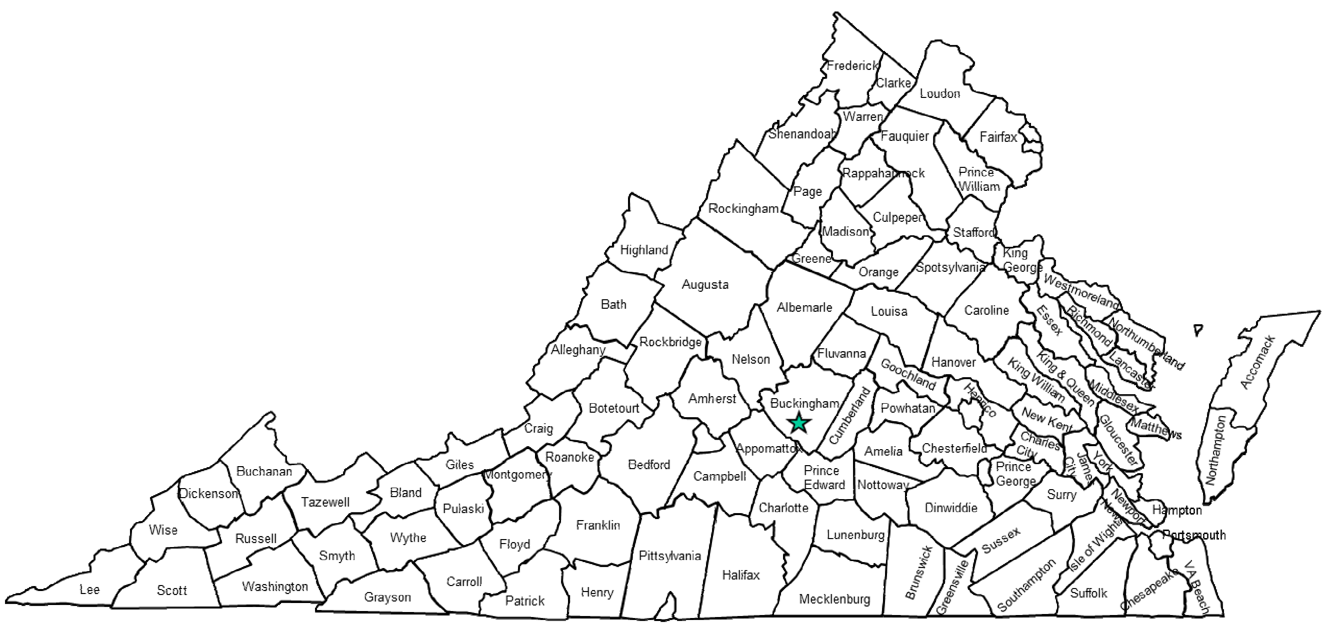


Figure 1. Study site was located in Buckingham County in the Piedmont physiographic region of Virginia.

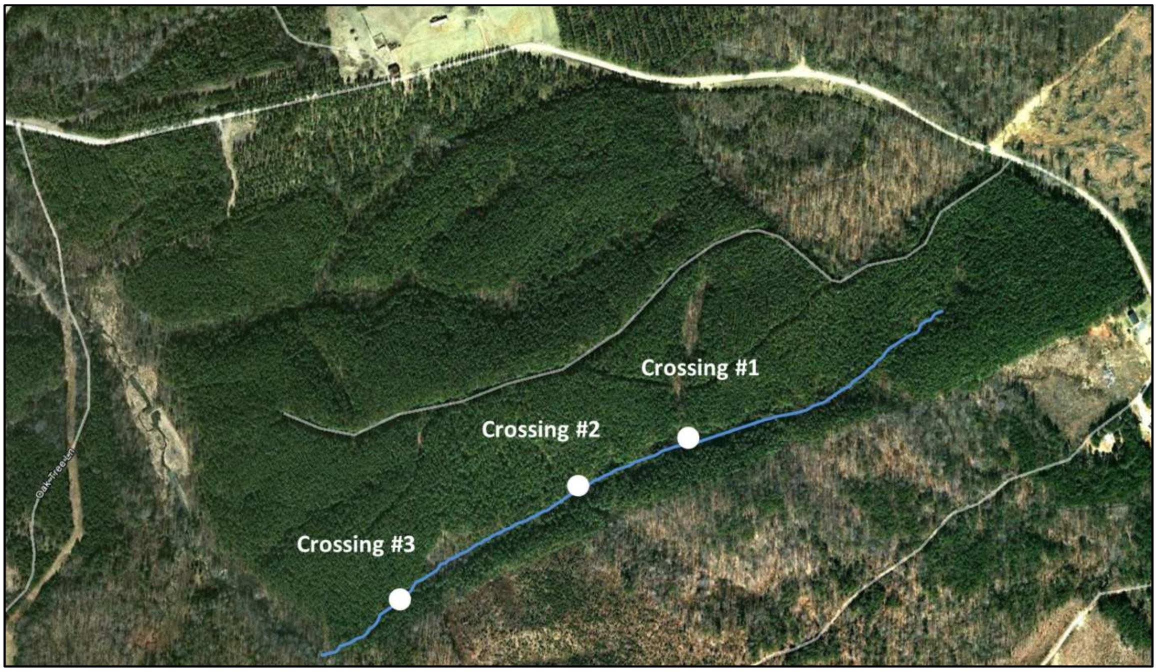


Figure 2. Pre-harvest aerial photo of study site. 2008. Source: Google Earth.

Table 1. Stream crossing approach characteristics.

Crossing	Treatment	Hectares harvested (crossed the stream)	Tonnes harvested (crossed the stream)	Average approach slope (%)	Maximum approach slope (%)
1	Mulch+silt	0.67	194.31	14	18
2	Slash	0.30	88.32	13	13
3	Mulch	0.17	48.28	10	18

Study Design

After harvest was completed and the skidder bridges were removed, three BMP closure treatments were randomly applied to the three skid trail stream crossings (6 approaches). The approaches were defined as the skid trail area on either side of the stream and within the SMZ.

The treatments were:

1. Slash – A grapple skidder pulled logging slash (tree tops and limbs) from decks and slash piles and placed it on the skid trail approaches (not in the stream). Slash was piled to depths ranging from 0.25 to 1 m (Figure 3).

Figure 3. Representative stream crossing approach that was closed with slash treatment.

2. Mulch – Grass seed, fertilizer, lime (to promote grass establishment), and straw mulch were spread on the approaches (not in the stream), with the mulch providing 100% coverage of bare soil. Each approach was covered with 10 bales of mulch, equating to 20 bales per crossing (Figure 4).

Figure 4. Representative stream crossing approach that was closed with mulch treatment.

3. Mulch + silt fence – Silt fence was installed <1 m from the stream bank, parallel to the stream on both sides of the stream channel. Installation included burial of the fence into a trench in order to effectively trap sediment

carried by overland flow. In addition, grass seed, fertilizer, lime, and straw mulch were spread on the approaches (not in the stream), with the mulch providing 100% coverage of bare soil. Each approach was covered with 10 bales of mulch, equating to 20 bales per crossing (Figure 5).

Figure 5. Representative stream crossing approach that was closed with mulch + silt fence treatment.

The study was conducted on a first order intermittent stream. At each stream crossing, two automated water samplers, either ISCO 3700 (Teledyne Isco, Inc. 4700 Superior St. Lincoln, NE 68504) or Sigma 900MAX (Hach Company, P.O. Box 389, Loveland, CO 80539) were installed, one approximately 10 meters upstream and one 10 meters downstream from the crossing (Figure 6). The water samplers were installed after harvest (for equipment safety and logistical reasons), but before the closure treatments were applied. The water samplers were placed uphill from the streambanks and each was powered with a 12-volt marine battery and chained to a nearby tree. Plastic tubing connected the sampling pump to the intake filter. The weighted intake filters were positioned in riffle sections of the streams and were attached to the gravel streambeds with landscaping staples. The depth of the stream was about 20 cm (8 in) during baseflow conditions. The automated water samplers were programmed to collect one 500 mL sample per day at 10 AM. After the sample was pumped to the housing and dispensed into its designated bottle, the tubing was purged of water. Each sampler was limited to 24 water samples, thus the retrieval of the samples occurred every three weeks and samples were taken to the lab for analysis. Water quality was evaluated by analyzing the samples for total suspended solids (TSS) using the method outlined by Eaton et al. (2005). Data collection continued for 10 months from the initial collection date.

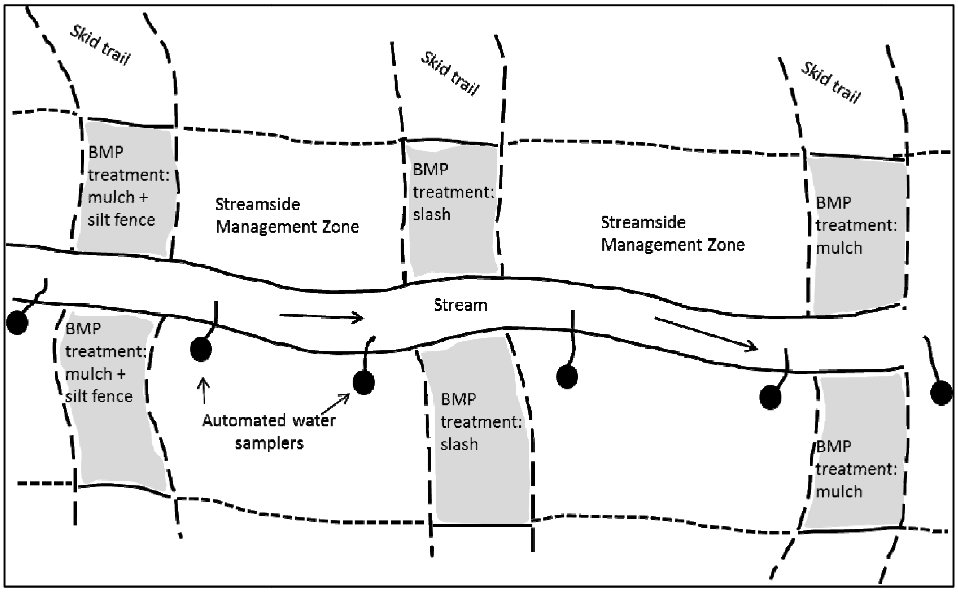


Figure 6. Idealized diagram of study site. Not to scale

Daily precipitation data were collected from National Oceanic and Atmospheric Administration (NOAA) weather stations that were closest to the tract. The water sampler which was the farthest downstream was outfitted with a flow meter, and hourly flow data was collected. This data was correlated with rainfall and used for the calculation of sediment loading. Each day, a rainfall value, flow values, an upstream TSS value, and a downstream TSS value for each crossing were collected.
Treatment costs were incurred and reported by the loggers responsible for installation. Costs included both materials and labor. The treatments which did not require a material cost were based on labor and machine time only (i.e., slash application). Reported costs were averaged for each treatment.

Statistical Analysis

Daily sediment loading was calculated at each stream crossing, using downstream TSS values and flow data. Data were analyzed for significance using JMP Statistical Discovery Software (JMP, Version 9 2010). Data were not normally distributed, thus the Wilcoxon Test was used to detect treatment differences (Ott and Longnecker 2010).

Results and Discussion

The mulch treatment was considered the most effective BMP closure treatment. The mulch and slash treatments were statistically different, with the mulch outperforming the slash (Table 2). The mulch and mulch + silt fence was also statistically different, with the mulch outperforming the mulch + silt fence (Table 2). This was the case particularly between days 200-300, where rainfall increased during the spring season (Figure 7). During higher rainfall events, the potential for erosion to enter the stream at the stream crossing is greater (Rothwell 1983).
Table 2. Stream crossing closure treatment differences for downstream sediment loads for each pair of treatments. Alpha = 0.05, q* = 1.959. Days 1-20 were pre-treatment data and were removed from the analysis.

Treatment		Treatment	Score Mean Difference (relative rank)	Standard Error Difference	Z	p-value
Mulch	vs.	Slash	23.52	9.69	2.425	0.0153*
Mulch + silt fence	vs.	Slash	2.04	9.31	0.219	0.8265
Mulch + silt fence	vs.	Mulch	-21.39	9.16	-2.335	0.0195*

During the study, the largest downstream sediment loading value for slash was 0.79 tonnes/day, for mulch it was 0.34 tonnes/day, and for mulch + silt fence, the largest value was 1.02 tonnes/day. The time at which the most rainfall occurred, the treatments performed as follows: mulch > slash > mulch + silt fence (Figure 7). Although at times, the slash and the mulch + silt fence treatments switched positions, the mulch treatment consistently had the lowest sediment inputs in the stream.

The mulch treatment was the most effective treatment because it produced the smallest amount of sediment downstream of the crossing. The almost complete coverage of bare soil, as well as the establishment of vegetation acted to prevent and/or slow down erosion that would otherwise occur at the stream crossing approach. It was unexpected that the treatment with silt fence was the least effective. However, this traditionally-used method of erosion control was positioned directly adjacent to the stream channels, causing more harm than good to the stream bank. The installation of silt fence requires that a trench be dug and the fence buried in it. This disturbance required for its installation outweighed its benefits within such close vicinity to the stream. We do not recommend using silt fence at stream crossings if disturbances are created at the stream bank.

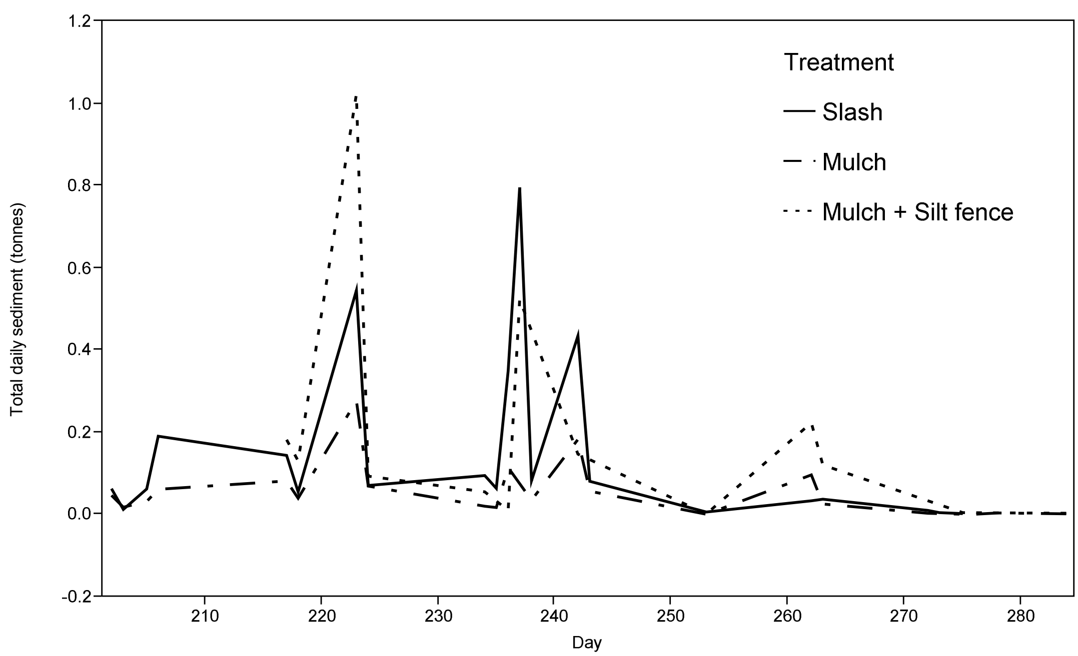


Figure 7. Time since harvest analysis of total daily sediment downstream from each crossing. Time period shown is days 200-300, which included the season with the largest rain events.

Table 3. Approximate treatment costs per stream crossing.

Treatment	Materials (cost)	Labor (cost)	Total Cost per Stream Crossing
Slash	Logging slash n/a	Skidder machine time $120	$120
Mulch	Straw mulch (20 bales) $100 Lime $5 Fertilizer and seed $5	Dozer machine time $90 Manual labor $80	$280
Mulch + Silt fence	Straw mulch (20 bales) $100 Lime $5 Fertilizer and seed $5 Silt fence $25	Dozer machine time $90 Manual labor $120	$345

Slash was the least expensive treatment option (Table 3). In this case, the majority of the slash was moved during normal logging operations, during the last few turns of the skidder, also known as integrated slash (Sawyers 2012). This minimized the need for extra machine and labor time after harvest was complete. Since the slash was on-site, the only cost incurred for this treatment was machine and labor time. The next best option was the mulch treatment, which cost approximately $280 per crossing, and consisted of grass seed, fertilizer, lime, and straw mulch. The most expensive treatment was the mulch + silt fence treatment, which consisted of grass seed, fertilizer, lime, straw mulch, and silt fence. Not only is the silt fence treatment more expensive, but it also requires more installation time and results show it to least effective for preventing erosion.

Literature Cited

Anderson, C.J. and B.G. Lockaby. 2011. Research gaps related to forest management and stream sediment in the United States. Environ. Manage. 47:303-313.

Archey, W.E. 2004. The National Association of State Foresters: 2004 progress report-statewater resources programs for silviculture. The National Association of State Foresters, Washington, DC.

Arthur, M.A., Coltharp, G.B. and D.L. Brown. 1998. Effects of best management practices on forest stream water quality in eastern Kentucky. Journal of the American Water Resources Association (JAWRA) 34(3):481-495.

Aust, W.M. and C.R. Blinn. 2004. Forestry best management practices for timber harvesting and site preparation in the eastern United States: an overview of water quality and productivity research during the past 20 years. Water, Air, and Soil Pollution 4(1):3-36.

Clinton, B.D. and J.M. Vose. 2003. Differences in surface water quality draining four road surface types in the Southern Appalachians. Southern Journal of Applied Forestry 27(2): 100-106.

Eaton, A.D., Clesceri, L.S., Rice, E.W., Greenberg, A.E. and M.H. Franson. 2005. Total Suspended Solids Dried at 103-105°C. *In* Standard Methods for the Examination of Water and Wastewater; American Public Health Association. Washington, DC: APHA.

Great Lakes Environmental Center. 2008. National Level Assessment of Water Quality Impairments Related to Forest Roads and Their Prevention by Best Management Practices. Final Report. Report prepared for US Environmental ProtectioAgency, Office of Water, Contract No. EP-C-05-066, Task Order 002, 250 p.

Grace, J.M. 2005. Forest operations and water quality in the South. Transactions of American Society of Agricultural Engineers 48(2):871-880.

Grushecky, S.T., Spong, B.D., McGill, D.W. and J.W. Edwards. 2009. Reducing sediments from skid roads in West Virginia using fiber mats. Northern Journal of Applied Forestry 26(3):118-121.

Henley, W.F., Patterson, M.A., Neves, R.J. and A.D. Lemly. 2000. Effects of Sedimentation and Turbidity on Lotic Food Webs: A Concise Review for Natural Resource Managers. Reviews in Fisheries Science 8(2):125-139.

Jackson, C.R., Martin, J.K., Leigh, D.S. and L.T. West. 2005. A southeastern piedmont watershed budget: evidence for a multi-millennial agricultural legacy. Journal of Soil and Water Conservation 60(6):298–310.

JMP, Version 9. SAS Institute Inc., Cary, NC, 2010.

Lane P.N.J. and G.J. Sheridan. 2002. Impact of an unsealed forest road stream crossing: water quality and sediment sources. Hydrological Processes 16(13):2599–2612.

Marcus, W.A. and M.S. Kearney. 1991. Upland and coastal sediment sources in a Chesapeake Bay estuary. Annals of the Association of American Geographers 81(3):408-424.

Nutter, W.L. and J.E. Douglass. 1978. Consequences of harvesting and site preparation in the Piedmont. *In* Proceedings: A symposium on principles of maintaining productivity on prepared sites, 65-72. Atlanta, GA: U.S. Department of Agriculture, Forest Service.

Ott, R.L. and M. Longnecker. 2010. The Wilcoxon Rank Sum Test, in: An Introduction to Statistical Methods and Data Analysis, sixth ed. Brooks/Cole, Belmont, CA, pp. 305-314.

Patric, J.H. 1976. Soil erosion in the Eastern forest. Journal of Forestry 74(10):671-677.
Rothwell, R.L. 1983. Erosion and sediment production at road-stream crossings. Forestry Chronicle 59(2):62-66.

Sawyers, B.C., Bolding, M.C., Aust, W.M. and W.A. Lakel, III. 2012. Effectiveness and implementation costs of overland skidding closure techniques in the Virginia Piedmont. Journal of Soil and Water Conservation 67(4):300-310.

Swift, L.W. and R.G. Burns. 1999. The three Rs of roads: redesign, reconstruction, restoration, Journal of Forestry 97(8):40–44.

USDA Natural Resources Conservation Service 2011. Web Soil Survey. http://websoilsurvey.nrcs.usda.gov/app/ .

US Environmental Protection Agency 2003. Nonpoint-source pollution: The nation's largest water quality problem. Washington, D.C.: US Environmental Protection Agency, Office of Water, Nonpoint Source Control Branch. http://www.epa.gov/owow/nps/facts/point1.htm

Wear, L.R. 2012. Skid trail stream crossing closure techniques for protecting water quality. Master of Science Thesis, Virginia Tech. 73 p.

Single Wide Tires for Log Trucks

Jeff Wimer[1] and John Sessions[2]

Abstract

Single wide tires for log trucks offer potential savings in fuel through decreased rolling resistance and increased log volume per load through reduced tire and wheel weights. Their use is steadily increasing by on-highway fleets. We provide an overview of the opportunities and challenges for introducing single wide tires for logging.

Keywords: Log hauling, truck fuel economy, transportation cost efficiency

Introduction

On July, 20, 1964, Weyerhaeuser Company (Ekse, 1965) at their Longview (Washington) Tree Farm, tested single wide tires on off-highway logging trucks on gravel logging roads. The purpose was to test the hypothesis that wide tires (23 x 23.5) require less rock than dual tires (12 x 24), due to their lower dynamic loading on the road bed. The study concluded that for their conditions, use of wide tires would save 15-20 percent on rock depth. Interestingly, there was a side benefit of reported savings of about 10 percent in fuel consumption and there was a lower frequency of flat tires. But who cared? Diesel was about $.20 per gallon, tires were the largest cost center, followed by labor with fuel a distant fourth.

Fast forward 40 years. The tire manufacturers are back with a new and improved single wide tire design (Figure 1) that provides claims of up to a 10% reduction of fuel usage. With On-highway diesel periodically topping $4.00 per gallon, fuel is now the largest cost center labor is second, and tires are fourth. With some log trucks using $60,000 per year in fuel and hauling longer distances to deliver product is it time to revisit the application of single wide tires in log truck use?

Fuel Savings

Savings in fuel from reduced rolling resistance depends upon tread depth and the number of single wide tires on the truck. Claims of fuel savings vary from 6 – 10%. These claims come from widely different sources including EPA (Bachman et al., 2005), SAE supported literature (Fitch, 1994), and truck maintenance records from a local log-hauling cooperator who has been running wide tires for several years. With a truck hauling 80,000 miles per year, diesel at $4.00 per gallon and the truck currently

[1] Department of Forest Engineering, Resources and Management. Oregon State University Corvallis, Oregon 9733. Jeff.wimer@oregonstate.edu

[2] Department of Forest Engineering, Resources and Management. Oregon State University Corvallis, Oregon 9733. john.sessions@oregonstate.edu

averaging 5 mpg, a 6% savings equates to a savings of $3840 per year. A 10% savings equals $6400 in savings. Low rolling resistance single wide tires are identified as an important contributor to the EPA SmartWay Technologies program (EPA 2012)

Figure 1. Single wide tires on a log truck tractor.

Weight Reduction

The reduction in truck tare weight is about 150 pounds per single wide tire and rim. Trucks with 8 single wide tires have a weight reduction of about 1200 lbs. Operators who are paid on a per ton or per mbf basis could see annual revenue increase of approximately 2 - 3%. With operations receiving $750 per day and operating 200 days per year this revenue increase equates to a $3000 - $4500 increase in revenue due to increased load.

Tire Life and Maintenance

The largest influence on tread life, other than the operator, is the percentage of unpaved road miles. One cooperator showed tire life for single wide tires in the range of 30,000 – 80,000 miles depending on percentage of paved miles. This is similar to tire life for conventional log truck tire applications. Sidewalls have not been an issue in the current single-wide tire design. Our cooperator reported no sidewall failures. All flat tires reported were because of face related injury. Flat tires for our cooperator occurred about once every 3 months of operation per truck. One major problem with single wide flats, where the tire goes completely flat, is that the truck is down until roadside assistance is available. With conventional tires a driver may be able “to limp” an *empty* truck to town for flat repair. This additional downtime could result in the loss of loads as well as the expense of a road call. Tire pressure monitors would be important to detect leaks to prevent roadside flats so that tire maintenance could take place at the shop rather than in the field.

Tire Performance

Drivers reported that the ride for single-wide tires was not significantly different that of a truck equipped with conventional tires. One exception was where the operation was on muddy roads. With the single-wide design there is no central cavity between the tires to help disperse the mud and the mud accumulates in front of the tire. This, in effect, causes the mud to dam up in front of the tire thereby reducing traction. Reducing tire pressure might increase traction, but tire load ratings would need to be approved by the tire manufacturer and traction data for wide tires at reduced pressures is not available. Wide tires can be reportedly recapped two to three times if the carcass is not damaged.

Retrofitting Existing Trucks

Retrofitting an existing truck with single wide tires does not require any changes to the axle hub assembly. The single-wide rims mount onto existing stud configurations. Several truck manufacturers have a single wide option when ordering new trucks. A single wide tire costs approximately the same as two conventional tires. The fleet price for a new truck and trailer with wide tires is reportedly slightly less than with conventional tires. Retrofitting an existing truck will require an investment in rims. There is some evidence that on-highway trucks with wide tires have a higher resale price that with conventional tires.

Putting It All Together

Are savings in fuel and reduced weight enough to justify the use of super singles in an unpaved road hauling application? Problems may arise in traction, when hauling in mud and snow or with flat tires and cap-ability of the tires. Early reports from cooperators, who run a large percentage of on-highway miles, show some promising results.

An option to running wide tires on the truck and tractor is to run wide tires on the trailer only. Trailer tires do not need the aggressive tread designs that traction tires require. Tread depth can be less, although tire life to retread will be shorter. At least one chip van manufacturer is equipping trailers with single wide tires for forest biomass recovery.

We have developed a prototype spreadsheet program to assist transport managers in comparing the cost efficiency of single wide to dual tires

References Cited

Bachman L. J. , A. Erb, and C. Bynum. 2005. Effect of single wide tires and trailer aerodynamics on fuel economy and NOx emissions of Class 8 Line-Haul tractor-trailers. SAE Paper No. 05CV-45, 9 p.

Ekse, M. 1965. Wide single versus dual tires: A logging road test. Department of Civil Engineering, University of Washington. Prepared for USDA Forest Service PNW Research Station. 18 p.

EPA, 2011.
http://www.epa.gov/smartway/documents/partnership/trucks/partnership/techsheets-truck/EPA-420-F10-041.pdf

EPA 2012. SmartWay Technology Program. Accessed on August 12, 2012 at http://www.epa.gov/smartway/technology/tires.htm

Fitch, J. 1994. Motor truck engineering handbook. Fourth edition. Society of Automotive Engineers, Warrendale, PA. 443 p.