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Mechanised Pine Thinning Harvesting Simulation: Productivity and Cost Improvements as a Result of Changes in Planting Geometry

Simon A. Ackerman, Stefan Seifert, Pierre A. Ackerman, Thomas Seifert

Abstract

Traditionally, the removal of entire rows at regular intervals through thinning compartments has been applied to facilitate access to mechanised timber harvesting operations in South Africa. These row thinnings have essentially involved the removal of every 7th row in a standard 2.7×2.7 m planting regime, resulting in a machine trail width of 5.4 m and a theoretical distance to the furthest tree of 8.1 m.

A simulation study, based on alternative planting geometries, investigated the effect on harvesting in terms of harvesting productivity, system costs and impact on stand structure. Compartments of different planting geometries ranging from 2.7×2.7 m to 2.5×2.9 m, 2.4×3 m and 2.3×3.1 m at two thinning reference ages were simulator generated. These compartments were then simulator thinned and harvested in the simulation.

Results showed that the boom reach of the harvester is optimised by extending row removal from the 7th to the 9th row. At the same time, machine trail length per hectare was reduced by 20%. This creates more productive area for tree growth, potentially reduced residual stand impacts, and increases the proportion of selectively harvested trees per hectare. The increased distance between row thinning removals enhanced the potential volume harvested trail length (m^3/m) and in turn led up to a 8% increase in harvesting productivity, up to a 21% increase in forwarding productivity and a reduction in total costs of up to 7% when changing planting geometry from 2.7×2.7 m to 2.3×3.1 m and 2.4×3.0 m, for first and second thinning.

Keywords: harvesting, simulation, thinning, planting geometry, productivity, system costing, optimisation

1. Introduction

The advent of more advanced mechanised timber harvesting systems has identified the potential of possibly modifying planting geometries and thinning practices (Bredenkamp 1984). One of the alternatives considered is that of row thinnings where an entire row or rows are removed at predetermined intervals throughout the compartment. However, a balance needs to be achieved between improved harvesting efficiency and potential losses by eliminating a portion of the selective thinning process (Bredenkamp 1984).

It had been found that, if the execution of these two entirely different thinning systems were not well aligned (i.e. selective thinning is carried out first without identifying the trees to be removed in the rows removals), it results in an irregular stand structure along the removed rows (Ackerman et al. 2013). Suboptimal tree volume growth and tree form is a further consequence (Ackerman et al. 2013).

The study simulated both felling and subsequent timber extraction operations in virtually constructed stands, where both access rows had been removed and selective thinning applied between these rows. The proviso was that the simulation exercise had to maintain regular stand structure to satisfy optimal stand development.

The use of an aggregation index (*R*), as proposed by Clark and Evans (1954), was applied as a measure of irregularity in the stands and, as an indicator of stand occupation efficiency, appears to have not been applied in South Africa forestry before. Similarly the application of computer simulation, now widely used in forest operations research worldwide (Asikainen 1995, 2001, 2010), was used to test different planting geometries on thinning harvesting productivity and cost. Simulation offers effective systems evaluation potential as alternatives (harvesting systems and management regimes) can be tested virtually without actual implementation of the said systems in the field (Talbot et al. 2003, Hogg et al. 2010, Pretzsch et al. 2002a).

2. Objective

The objective of the study was to quantify the consequences of alternative planting geometries to the conventional 2.7×2.7 m on mechanised cut-to-length CTL) harvesting. The study questioned whether the modification of planting geometry:

⇒ reduced machine trail length per hectare still maintaining suitable access for the harvesting machines;

⇒ maintained compartment tree spacing regularity when simulated thinnings are done;

⇒ increased harvesting productivity with reduced harvesting system costs.

3. Materials and methods

In South African forestry research, information on tree characteristics in compartments (individual tree models for *DBH* and height based on competition) and time consumption models for harvesting (time study data) is scarce. For this reason and for the sake of generating simulated stands and time consumptions, species growth models and harvesting system time models were sourced from worldwide research. These models were assumed to be representative to the work done for the area of operation in this paper.

The procedure followed by the investigation into changing planting geometries and simulation is summarised as a flow chart in Fig. 1.

The study was based on simulated compartments that were generated based on real data to mimic a realistic tree size distribution. Spatial adjustments of virtually generated compartments were done through a computer simulator and were based on existing silvicultural prescriptions for saw-timber production (Table 1). Various alternative initial planting geometries returning the same final stems per hectare (*SPHA*) as prescribed were tested during the simulation. The simulated planting geometries took into account the physical characteristics and limitations of both the harvester and forwarder that were to be used in the study for the harvesting simulation of both first and second thinnings.

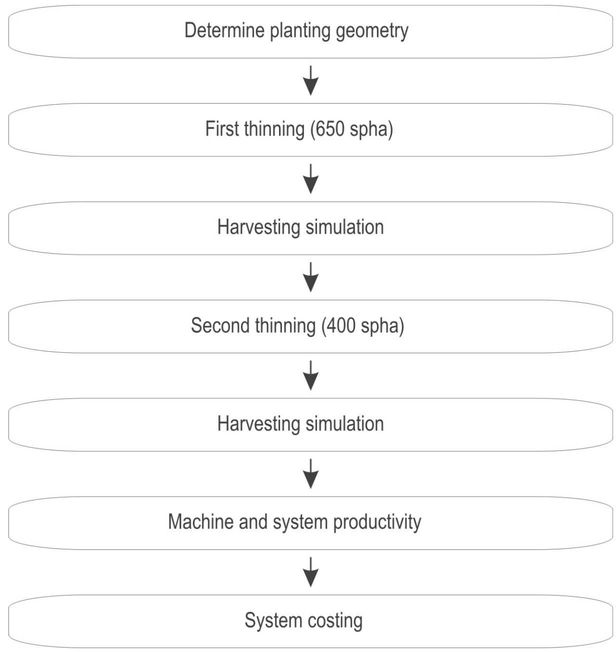

Fig. 1 Flow chart of the procedure followed for thinning and harvesting of compartments to maintain stand regularity

3.1 Determining tree characteristics to develop computer simulated compartments

The first step in the process to determine new planting geometries involved using pre-thinning enu-

Table 1 Standard establishment and thinning prescriptions in South Africa

Action	Desired density
Spacing (initial)	2.7×2.7 m
Stems per hectare planted (*SPHA*)	1371 *SPHA*
First thinning (age 8)	650 *SPHA*
Second thinning (age 13)	400 *SPHA*

meration tree data for compartments at thinning ages 8 and 13 years. This would establish the tree characteristics for each thinning age. The data set contained information for compartments of the same Site Index (SI_{20}) of 20. This data was used to develop *DBH* and height data representative of trees at the two particular thinning reference ages in a compartment.

However, applying this tree data randomly to a grid position does not sufficiently mimic the reaction of trees to growing space, nor to genetic variations. The reason is that compartment structure is not a purely random process. Competition between trees leads to a distinct tree dimension (Seifert 2003), relating to spatial pattern and compartment structure (Pretzsch 1997), where larger trees suppress their smaller neighbours. These spatial structures, resulting from competitive processes, had to be taken into account.

The structure generator, developed by Pretzsch et al. (2002b), was used for creating realistic diameter distributions and spatial distributions of trees. The results where validated with data from the existing trial plots. Tree diameters and heights were manually increased in proportion to the mean *DBH* and height based on pre-thinning enumeration data between first and second thinning. As a standard in South African growth and yield modelling, natural mortality is not taken into account in heavily thinned stands (Kotze et al. 2012), as evident between first and second thinning. This approach was applied to all the various alternative planting geometries investigated.

3.2 Determining optimal tree spacing and planting geometry

The second step involved matching machine size (and limitations) to planting geometries and adjusting these to various alternatives, while still maintaining the conventional tree spacing (2.7×2.7 m – 1370 trees/ha). Traditionally, machine trails for this geometry and others have been placed along the seventh row at right angles to tree rows. The removal of the seventh row for mechanised harvesting at this espacement results in a machine trail 4.5 m wide with a distance of 18.9 m between machine trails and an average required reach distance from either side of 9.45 m for the harvester boom.

By adjusting the distances of trees within and between the rows, the alternative planting geometries in Table 2 were proposed. Distance between machine trials, width of the machine trails and length of machine trail per hectare were used as criteria for selecting the spacing geometry to be used in the study.

Table 2 Breakdown of various planting spacings tested

Spacing *x – y*	Rows to be removed
2.7×2.7 m	7^{th} and 8^{th}
2.5×2.9 m	7^{th}, 8^{th} and 9^{th}
2.4×3.1 m	7^{th}, 8^{th} and 9^{th}
2.3×3.0 m	7^{th}, 8^{th} and 9^{th}

3.2.1 Machine limitations used to determine minimum planting spacing

A Tigercat harvester and forwarder *CTL* system was selected for this study (Table 3), since these machines were already in operation on the plantation where the data was collected. A trail width of 1 m wider than the machine was considered a feasible criterion for the different planting geometries to prevent damage to stems and to limit tree root disturbances (Table 3).

3.2.2 Planting geometries used in thinning and harvesting simulations

Using the machine limitations (Table 3), a selection system was developed to test the feasibility of various planting geometries from Table 2. The aim of the evaluation was to increase the distance between machine trails as much as possible (> 7^{th} row), thus reducing the machine trail length per hectare and ensuring the distance between machine trail was equal to or less than 20 m so that the harvester boom could reach trees from the machine trail (10 m to the middle of the inter-row). Matching these criteria would limit stand impact and maximise the harvester boom reach.

Even row (8^{th}) spacing was excluded from the simulations due to the centre point between two machine

Table 3 Machine limitations based on boom reach and machine track width for Tigercat harvesters and forwarders (Tigercat 2011)

Machine	Machine type	Boom reach, max	Boom reach, telescopic	Machine width	Payload
Tigercat H822c	Tracked harvester	8.91 m	11.07 m	3.43 m	–
Tigercat 1075B	Forwarder	7.83 m	N/A	3.30 m (bunk)	14,000 kg

trails possibly falling exactly on the same tree row. This would lead to sub-optimal harvesting, as the machine would essentially have to harvest four rows from one machine trail and only three from the other, thus not utilising absolute boom reach on one side.

3.3 Stand simulations

Following the process of matching machine specifications to various planting geometries, spatial tree lists containing x-and y-coordinates, *DBH* and height information of a 1.5 ha compartment were created in Excel. This was done for each of the planting geometries selected for the study. As a standard, the x-value always indicates the planting spacing used where a row of trees are removed for a machine trail. These were used as input into a specially designed simulation programme for thinning and harvesting, which was coded in the statistical language *R* (*R* Core Team 2012). A thinning from below was simulated for each stand. In this process trees that were marked as thinned were harvested by a harvesting simulator.

3.3.1 Thinning

Thinning from below generally concentrates on the removal of trees that are smaller in relation to the neighbours in the same growing area, thus relieving competition (Murray and von Gadow 1991, Kassier 1993, Pukkala and Miina 1998, Pretzsch 2009). The thinning was simulated with a rule based algorithm without stochastic components, as this would have created an additional source of variance. As a consequence of this deterministic approach, a repeated application of the algorithm to the same stand would have resulted in the removal of the same trees. Input for the programme was the targeted final stem number per hectare as related to the size of the plantation area to be thinned (N_{target}). The programme would evaluate neighbouring trees in relation to a particular tree to determine the growing area and the growth status of the centre tree. Within the programme, a defined local search radius for tree neighbours around a target tree from the N_{target} was calculated by estimating the average growing area per tree (Eq. 1).

$$A_{grow} = \frac{10,000}{N_{\text{target}}} \quad m^2 \qquad (1)$$

The local search radius for neighbouring trees was determined as 2.5 times the radius of a circle with the same area as A_{grow} (Eq. 2).

$$r_{\text{grow}} = \sqrt{(A_{\text{grow}} / 0)} \qquad (2)$$

Each of the tree neighbours within the search radius were used to calculate the local stem density, a *DBH* rank of the target (centre) tree to its neighbours, the proportion of the trees thinned to the target tree and a flag to mark if the distance to the nearest neighbour was less than r_{grow}. The local density was divided by the maximum density found in the stand. In order to make the values rateable, they were linearly transformed to be in a range between 0 and 1. This operation was done sequentially for all the trees in the stand.

Lastly, the values calculated were summed up to determine a potential for a tree to be removed in the thinning process. The summed values were then ranked, and the trees with the highest potential to be thinned to the target *SPHA* were marked »to be removed« (*TBR*) and the rest were marked »not to be removed« (*NTBR*) as flags in the output. To limit the effect of stand edges on thinning, a subset of 1 ha subset was taken from the middle of the stand.

A measure of aggregation (*R*) (Clark and Evans 1954) was used to determine the uniformity of the spacing in the stand after thinning. This measure of aggregation provided a test to evaluate the efficacy of the thinning algorithm. The particular data preparation and outputs for first and second thinnings are described below.

3.3.2 Simulated marking for thinning

Before the first thinning simulation, the rows that were thinned for the extraction trails (7^{th} or 9^{th} row) were removed from the dataset as this would be done in practice. The full data set, with these row trees removed, was then thinned and trees TBR to the desired stand density (including removed row trees) and *NTBR* trees were marked. The row trees were then reintroduced as *TBR* for further analysis. The resulting dataset with the marked trees (row thinned and selectively) was then used as input for the spatial harvesting simulation.

The second thinning simulation followed the same procedure, based on the stem numbers resulting from the first thinning operation except for the fact that no further row-thinnings were applied.

3.3.3 Harvesting

In the harvesting simulation process, the spatial reach of a harvester moving along a skid trail was simulated. Based on x-and y-coordinates of trees and the flag for *TBR* or *NTBR* trees, individual tree harvesting was conducted. Each individual skid trail location (defined by start and end) was used as an input to the simulator.

The output identified all the trees around the machine trail that could be reached by a 10 m boom, flagging them as accessible. If trees were attributed as ac-

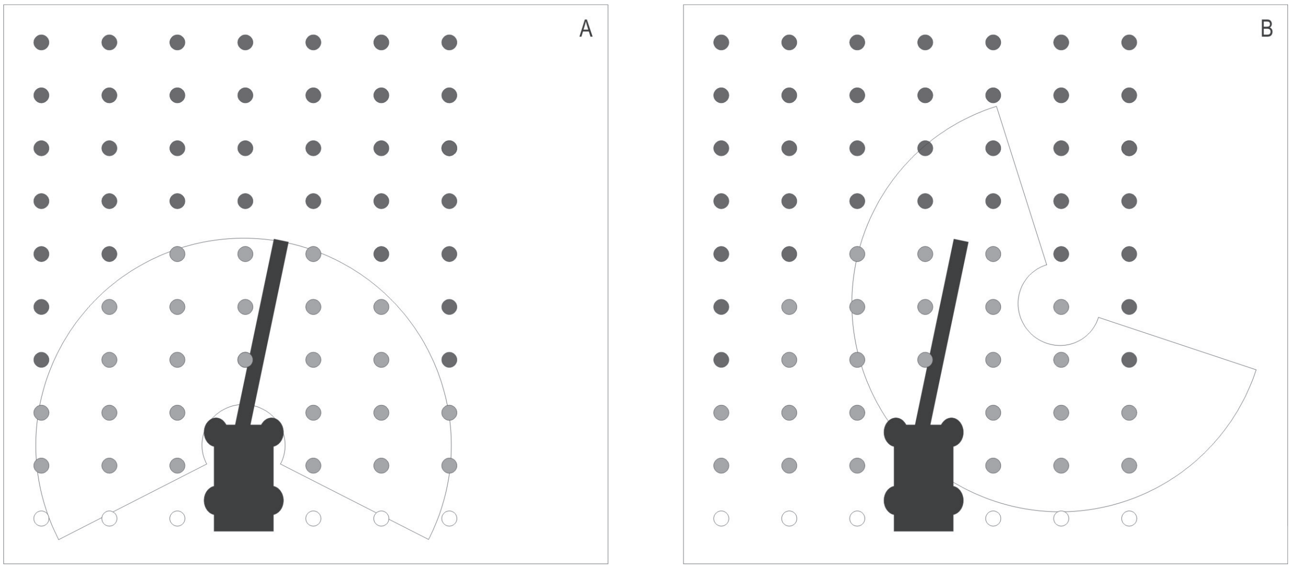

Fig. 2 a) harvester boom swath area and b) tree reach polygon

cessible and marked, *TBR* would be flagged as harvested for a particular harvesting stop. These stops were determined and calculated using a harvesting simulator.

The simulator was used to estimate the influence of spatial stand structure, extraction rows and stem number reduction on harvesting costs, and was designed and implemented using *R* (*R* Core Team 2012). This simulator was able to estimate the least number of position changes (harvesting position) of the harvester along a predetermined machine trail, and the number of trees harvested at each position.

The simulation was based on pure geometry using only the tree positions and the line on which the harvester moved on the machine trail. The reach of the boom and the tree coordinates were used to identify the optimal point from which most trees could be harvested, (Fig. 2a and b). From a start position, the harvester moved forward on the machine trail to the first optimal point at which most trees could be reached. From this first stop, once all the harvestable trees had been virtually harvested, the next optimal point was selected and the harvester moved forward to that point.

It was assumed that all trees in the polygon of Fig. 2a could be reached by the harvester head from the harvester position, the boom swath area. This, in reality may not be the case.

The next step was to define the area from which a specific tree could be reached by the harvester, the tree reach polygon (Fig. 2b). The tree reach polygon can be derived by calculating all possible harvester positions from which the harvester boom can reach the targeted harvestable tree. Geometrically this equals the inversion of the boom swath area in Fig. 2a. By intersecting the tree reach polygon with the machine trail, a new harvester stop line segment was created (Fig. 2). If the harvester was on this line segment, the boom could reach a particular tree.

The procedure followed a sequence to find the optimal position to harvest most trees from a position, without reversing, assuming that this would match the strategy of a real harvesting operator. Selection of the nearest trees to harvest and the line selection for each stop are shown in Fig. 3. The intersection of the tree reach polygon (Fig. 2b) with the machine trail line defines the line of the segment where trees will be harvested for that stop. All tree polygons (Fig. 3), which intersect the starting line segment, are added to the list of harvested trees. When no more trees intersect the segment, the maximum number of trees that can be harvested from that line segment has been found and the endpoint of this segment is used as the new harvester position.

These steps were repeated until the harvester had reached the end of this machine trail. This process allowed each harvested tree to be assigned to a specific harvester stop position. The total number of harvesting stops and the distance between stops were recorded. The accumulated distance along the machine trail was also calculated.

A tree volume, based on the *DBH* and height values, was assigned to each harvested tree using the Schumacher and Hall function with parameters for *P. patula* (Bredenkamp 2012). The volume per harvesting

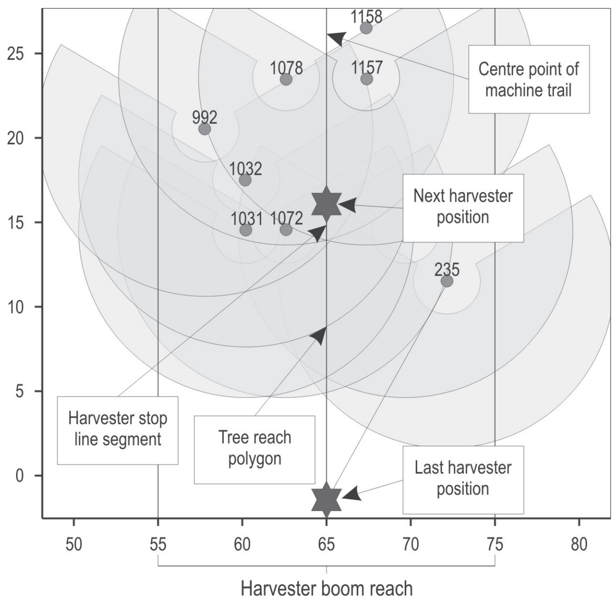

Fig. 3 Nearest tree to harvesting stop and tree selection polygons inverted and translated to the tree position

Table 4 Time element calculations used to determine time consumption in simulated operation

	Element		Time calculation
Harvester	1 Driving		33 m/cmin (Eliasson et al. 1999)
Harvester	2 Harvesting	a) Moving boom to cut	0.1 cmin/tree (Nurminen et al. 2006)
Harvester	2 Harvesting	b) Felling	$t=0.093+0.101x$ (Nurminen et al. 2006) t=time (cmin/tree); x=volume of the tree
Harvester	2 Harvesting	c) Processing	$t=0.0359+1.1368x$ (Nurminen et al. 2006) t=time (cmin/tree); x=tree volume
Harvester	2 Harvesting	d) Boom in	0.049 cmin/tree (Nurminen et al. 2006)
Harvester	2 Harvesting	e) Clearing debris	0.017 cmin/tree (Nurminen et al. 2006)
Forwarder	1 Travel empty		56 m/cmin (Nurminen et al. 2006)
Forwarder	2 Load	First thinning	$t=2.022+\frac{0.211}{x}$ (Nurminen et al. 2006) t=time (cmin/tree); x=volume of the tree
Forwarder	2 Load	Second thinning	$t=2.777+\frac{0.211}{x}$ (Nurminen et al. 2006) t=time (cmin/tree); x=volume of the tree
Forwarder	3 Travel partially loaded		26.7 m/cmin (Nurminen et al. 2006)
Forwarder	3 Travel loaded		43.9 m/cmin (Nurminen et al. 2006)
Forwarder	4 Unloading		*0.569 cmin/m^3 (Nurminen et al. 2006) *Based on mixed sawtimber loads

stop was totalled for each row with the distance between harvesting stops and accumulated distance travelled along the machine trail.

3.4 Harvester and forwarder productivity

Volumes harvested at each harvesting stop were calculated. In order to determine the productivity of the harvesting system, the time taken to harvest and forward the timber needed to be determined. Time consumption was determined using existing time study functions with the harvesting and forwarding time consumption broken up into time elements. Due to actual time studies not being within the scope of the project in South Africa, element times and machine speeds were taken from studies by Eliasson et al. (1999) and Nurminen et al. (2006), respectively, for Nordic countries (Table 4).

Based on the output from the harvesting simulations, a harvested volume for each harvesting stop was allocated for each machine trail that would have been harvested. The forwarder would then load timber from each of these harvesting stops. The simulated work method for each machine is described as follows.

A harvester cycle starts at the base of the first machine trail and moves to the first harvesting stop as determined by the harvesting simulation. All the trees for that particular harvesting stop are assumed to be harvested and processed. Once the harvesting is complete, the next cycle starts with the machine moving north to the next harvesting stop (Fig. 4). At the end (highest x-and y-coordinate) of the machine trail, the machine moves to the base of the next machine trail and the simulation starts again.

As with the harvester (Fig. 4), the forwarder would move into the stand from the start of machine trail one. It would then travel empty along the trail to the first timber stack, load and travel partially loaded to the next stack and continue loading. This was repeated until the forwarder was fully loaded to its capacity of 20,000 kg or 18.86 m^3 (Table 3) for a Tigercat 1075B. This figure is based on a direct conversion of weight to volume of 1.06 tonnes to m^3 provided by Bredenkamp (2012).

Once the forwarder reaches the end of the machine trail, it is moved to the next one. At the point where the forwarder is full, it stops loading and travels full back down the machine trail to the nearest road where timber is unloaded. The machine then travels unloaded back to the last unfinished stack or a new stack to continue the process.

Information gathered from the machine work methods and the time models was used to calculate

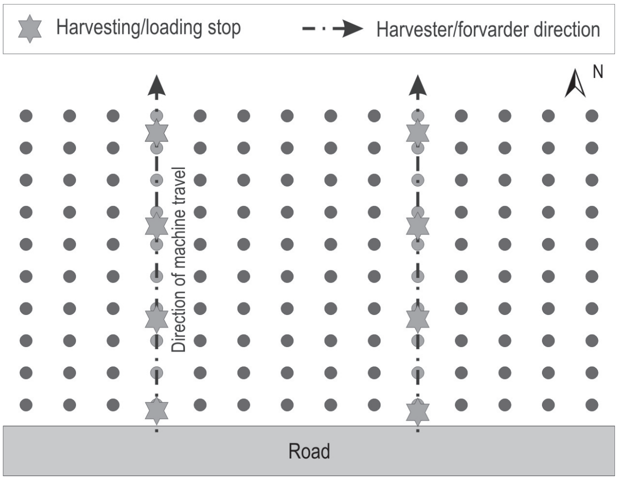

Fig. 4 Simulation steps for harvester and forwarder for harvesting and loading time allocation

the time taken to harvest 1 m^3 of timber for each scenario and it was then compared to the standard spacing (2.7×2.7 m). Inputs to fixed and variable costs were based on standard industry data and input from the machine dealers. Operator, licensing, insurance, other miscellaneous costs and delays were not taken into account. Based on this information (Table 5), machine costs were determined for each scenario using a standard machine costing model (Eliasson 2013).

3.5 Statistical analysis

A Levene-test for variance homogeneity was used to check for violations of the assumptions of homogenous variance between groups. Analysis of variance (ANOVA) was used to determine whether there were significant differences between the test criteria in planting geometries. In some cases, heteroscedasticity prohibited traditional *t*-tests and ANOVA. A non-parametric Welch's *t*-test was used in these cases; this test is more robust against homoscedasticity violations. Subsequently, to determine further differences between planting geometries, a Bonferroni multiple hypothesis test or a Tamhane *T*2 test were applied, depending on homoscedastic or heteroscedasticity of variance respectively (Lyman Ott 1990).

Table 5 Costs (South African Rand) and costing assumptions for machines and attachments used in system costings (G. Olsen pers. comm. 2012, J. van Heerden pers. comm. 2013)

Item	H822C Harvester	1075B Forwarder
Fixed cost inputs		
Machine cost	R4'056'754.00	R4'728'538.00
Harvesting attachment	R1'319'985.00	No attachment
Machine life	18,000 hrs	18,000 hrs
Harvesting attachment life	18,000 hrs	NA
Salvage cost machine, %	10	10
Salvage cost attachment, %	0	NA
Interest rate, %	9	9
Insurance, registration, set-up and garaging costs	R 0.00	R 0.00
Variable cost inputs		
Fuel costs	R 11.60 (Feb, 2013)	R 11.60 (Feb, 2013)
Fuel consumption	28 l/hr	12 l/hr
Oil cost of fuel cost	20%	10%
Maintenance cost machine, %	100	100
Maintenance cost attachment, %	100	NA
Number of tracks/tyres	2	8
Cost per track/tyre	R 155,000.00	R 42,000.00
Life of track/tyres	9000 hrs	8000 hrs
Cutter bar life	61.2 PMH	NA
Cutter bar cost	R 1500.00	NA
Chain life	38.25 PMH	NA
Chain cost	R 500.00	NA
Sprocket life	612 PMH	NA
Sprocket cost	R 1100.00	NA
Operator inputs	–	–
Operators per shift	1	1
No operator costs were taken into account		
Productivity inputs		
Working days per year	240	240
Shifts per day	2	2
Hours per shift	9	9
Productivity per hour	Based in time study information	Based in time study information
Machine utilisation	85%	85%

4. Results

4.1 Harvesting thinnings from optimised stand structure

4.1.1 Determining the optimal tree geometry

The planting geometry selection process found that the following planting geometries 2.5×2.9 m, 2.3×3.1 m and 2.4×3.0 m (Table 6), were suitable alternatives for the conventional 2.7×2.7 m geometry; i.e. the control.

Table 6 Acceptable planting geometries based on rows removed, machine trail length and closest tree distance

Planting geometry m×m	Machine trail width m	Distance to furthest tree m	Row remove machine trail	Spacing between trails m*	Trail length ha^{-1} m	Number of rows removed ha^{-1}
2.7×2.7	5.4	9.45	7th	18.9	599.4	6
2.5×2.9	5.0	10.0	9th	22.5	500.0	5
2.3×3.1	4.6	9.2	9th	21.6	504.0	5
2.4×3.0	4.8	9.6	9th	20.7	506.0	5

*Measured from the mid-point of the machine trails

The alternatives reduced the length of machine trail ha^{-1} by between 99.4 m/ha and 93.4 m/ha. The number of tree rows removed per hectare was reduced by adjusting the width between the skid trails in all cases. In all the proposed planting geometries, the distance to the furthest tree was within the maximum reach of the harvester boom (10 m).

In order to test the efficiency of the thinning in maintaining an evenly distributed tree structure, a Clark and Evans aggregation (*R*) index was carried out on the tree distribution before and after thinning. The results of this analysis appear in Table 7.

Table 7 Clark and Evans (*R*) index for stands before and after thinning

Thinning	Planting geometry m×m	Clark and Evan aggregation index, *R*	
		Before thinning	After thinning
First	2.7×2.7	1.863	1.098
	2.5×2.9	1.760	1.132
	2.4×3.0	1.701	1.124
	2.3×3.1	1.641	1.156
Second	2.7×2.7	1.425	1.126
	2.5×2.9	1.398	1.100
	2.4×3.0	1.386	1.196
	2.3×3.1	1.641	1.156

4.1.2 Virtual harvesting of sample stands

Harvested volume data of the virtually thinned stands are shown in Table 8.

The results show the removed and remaining volume after each thinning, mean volume harvested at each harvesting stop and the mean distance between the harvesting stops. The mean differences between the different planting geometries (control vs potential scenarios) and the abovementioned criteria were compared.

4.1.2.1 Volume harvested per stop for each planting geometry

ANOVA analysis results for differences between the mean volumes harvested at each harvesting stop on machine trails for each planting geometry are shown in Fig. 5. Analysis of the data indicates that there were significant differences (p<0.05) between mean harvested volume at each harvesting stop for both first and second thinning.

A post hoc analysis using a Bonferroni multiple comparison test found that there were significant differences (p<0.05) between volume harvested at each stop for all of the geometries in the first thinning, except for the control and 2.4×3.0 m planting geometry. In the second thinning, there were no significant differences (p>0.05) between volume harvested at each stop for all of the geometries, except for a significant difference between 2.5×2.9 m and 2.3×3.1 m geometries.

4.1.2.2 Distance between harvesting stops for each planting geometry

A Welch *t*-test showed differences between the mean distances between harvesting stops on machine trails for each of the planting geometries (Fig. 6). The results of this test show that there were significant differences (p<0.05) between the distances between harvesting stops in both first and second thinning.

A Tamhane *T2* multiple comparison indicates significant differences between all the geometries except for the control and 2.4×3.0 m and the control and 2.3×3.1 m planting geometries in first thinning. In the second thinning, there were no significant differences between any of the combinations except for the control and 2.5×2.9 m planting geometry.

4.1.2.3 Harvesting time per harvesting stop for each planting geometry

ANOVA analysis was done on the first thinning data; it is, however, necessary to make a Welch *t*-test

Table 8 Harvested data before initial thinning and after first or second thinning

Thinning	Planting geometry m×m	Total volume, m^3/ha		Means per harvesting stop			
		Removed	Remaining	Volume, m^3	σ	Distance, m	σ
First	2.7×2.7	30.37	46.96	0.41	0.08	7.91	0.14
	2.5×2.9	27.66	48.13	0.26	0.03	5.19	1.02
	2.4×3.0	30.27	46.96	0.42	0.08	7.23	0.72
	2.3×3.1	28.56	47.46	0.51	0.05	9.05	0.43
Second	2.7×2.7	35.85	93.89	0.91	0.17	12.85	1.28
	2.5×2.9	35.31	90.87	0.76	0.20	10.38	1.39
	2.4×3.0	35.98	89.91	0.88	0.12	11.64	2.03
	2.3×3.1	39.02	90.57	1.00	0.12	11.86	1.12

on the second thinning data, too (Fig. 7). The results show that there were significant differences between the mean harvesting times at each harvesting stop. Significant differences were also found between all of the planting geometries in first thinning operations except for the control and the 2.4×3.0 m planting geometry (Bonferroni multiple comparison test). The second thinning showed no significant differences between the geometries, except between the 2.5×2.9 m and the 2.3×3.1 m geometries (Tamhane *T*2 multiple comparison test).

4.1.3 Time study and cycle times

Harvester cycles, volume and production achieved in the two thinning operations for each planting geometry are shown in Table 9. The number of cycles depended on the number of harvesting stops determined by the harvesting simulator.

In the first thinning, production was reduced between the control and the remaining planting geometries, while in the second thinning the opposite was true as an increase was evident. Forwarder cycles (Table 10) were limited by the load capacity of the

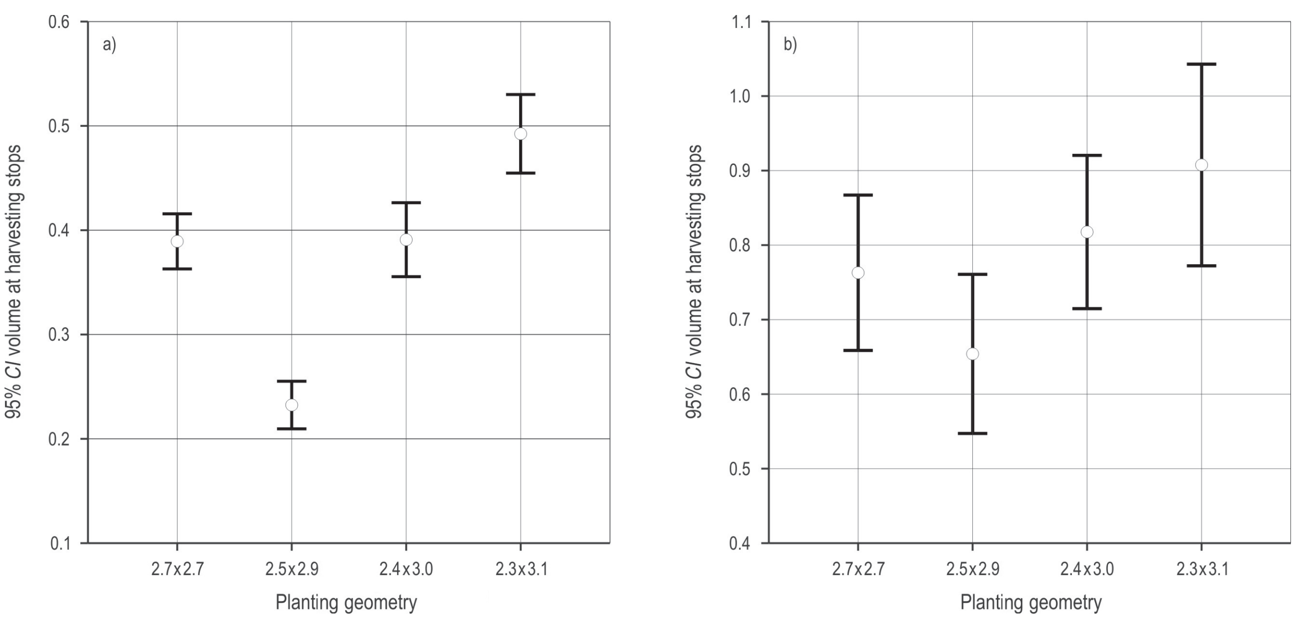

Fig. 5 Mean volume harvested for each stop (a) first thinning and (b) second thinning for each planting geometry

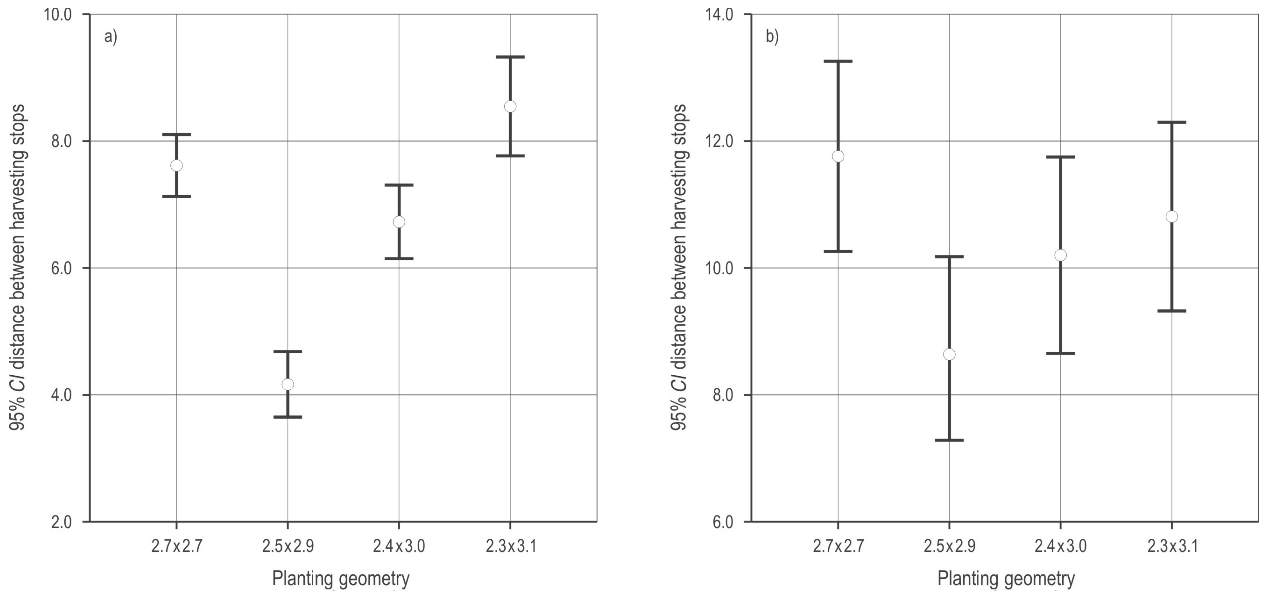

Fig. 6 Mean distance travelled between harvesting stops for (a) first thinning and (b) second thinning for each planting geometry

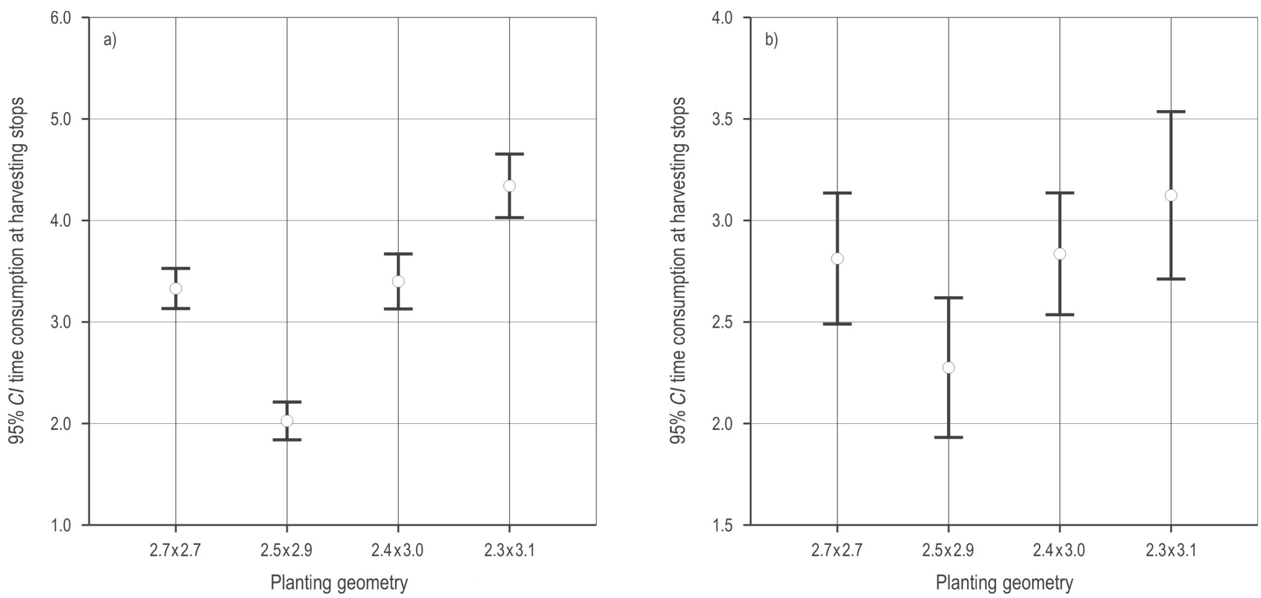

Fig. 7 Mean time consumption to harvest trees for each harvesting stop for first thinning (a) and second thinning (b) for each planting geometry

forwarder, and in most cases only one full load was possible (18.86 m^3) followed by a partial load. However, in the second thinning on the 2.3x3.1 m geometry, the additional volume to the machine trail led to two full loads and one partial third load being forwarded.

The lowest production was found in 2.5x2.9 m planting geometry; there was, however, a general increase in production from the control to the remaining planting geometries.

4.1.4 Machine and systems costing

The results of the machine costing and system costing are shown in Table 11.

In first and second thinning, the most expensive thinning operation (total costs) was for the 2.5x2.9 m planting geometry (*R* 306.76·m^{-3} and *R* 139.90·m^{-3}). In the first thinning, the cheapest system was that of the 2.3x3.1 m planting geometry (*R* 236.78·m^{-3}). The second thinning showed a reduction in cost between the control and the remaining planting geometries.

Table 9 Harvester total cycles, time taken, volume, productive machine hours (*PMH*) and volume per *PMH* for each geometry and thinning

Thinning	Planting geometry, mxm	Cycles	Time	Volume	*PMH*	m^3/PMH
First	2.7x2.7	78	259.66	30.75	4.33	7.11
	2.5x2.9	119	240.95	28.22	4.02	7.03
	2.4x3.0	72	244.74	28.50	4.08	6.99
	2.3x3.1	58	251.79	28.84	4.20	6.87
Second	2.7x2.7	47	132.2	35.70	2.20	16.20
	2.5x2.9	54	122.88	35.61	2.05	17.39
	2.4x3.0	44	124.78	36.20	2.08	17.41
	2.3x3.1	43	134.34	39.24	2.24	17.53

5. Discussion

5.1 Planting geometry changes

The alternative planting geometries that were compared in this simulation study (Table 6) indicated that a 20% reduction in machine trail length (from 599.4 m/ha to 500 m/ha) is possible when compared to the standard 2.7x2.7 m planting geometry (the control). A reduction in machine trail length has a number of advantages. Large gaps in the canopy, created by the cutting out of rows for machine trails in standard planting geometries, were reduced in size or limited. Furthermore, the likelihood of damage to residual trees during harvesting, purely because there are fewer trails, is also reduced (Hunt and Krueger 1960, Ohman 1970, Kromhout and Bosman 1982, Vasiliauskas 2001). However, in some cases, the distance between machine trails can cause the harvester head at full boom reach to lose control of the harvest tree. The resultant uncontrolled fall of the harvested tree can in some cases lead to residual tree damage (Fröding 1992 and Sirén 1992), if not monitored effectively.

It could be assumed, based on works of Warkotsch et al. (1994) and Bettinger et al. (1998), that fewer trails also resulted in reducing the potential of soil damage in terms of soil compaction and displacement. Similarly, the reduction in gaps in the canopy and irregular stand structure also reduce the negative effects on branchiness of the planted trees (Seifert 2003, Ackerman et al. 2013).

CTL harvesting, as applied in this study, generally shows reduced stand impact over tree-length and full-tree harvesting systems (Wang et al. 2005). This has great advantage over the traditional planting geometries.

5.2 Stand regularity after thinning

Alternative planting geometries and a thinning algorithm were developed to provide realistic thinning output while maintaining stand regularity. The aggregation index, (*R*) (Clark and Evans 1954) showed that the thinning algorithm was effective in terms of maintaining regular stand spacing.

The aim of the simulator was to avoid clustering of the trees and to maintain a (*R*) value higher than 1.0. All the aggregation index results were higher than this threshold (Table 7). This illustrates that the stands were thinned to a random distribution with no clustering.

5.3 Harvesting and forwarding productivity

5.3.1 Harvester

As expected, volumes per harvesting stop on machine trails increased with a reduction in machine trail length (Table 9). This was also closely associated with the distance between harvesting/loading stops and the time consumption for harvesting at each stop. In all cases, the 2.5x2.9 m planting geometry consumed less time than the control (2.7x2.7 m) and all other alternatives due to the lower volume per stop and shorter distances between stops. There were, however, many more stops per hectare than for the other geometries.

There was an overall increase in time consumed at each harvesting stop in the first as opposed to the second thinning. This was due to higher stem numbers (of lower piece volume) in the younger stand harvested. The individual tree volume in this simulation did not influence time consumption. The harvester boom movement related activities were the main driver of

Table 10 Forwarder cycle times and volumes per cycle for each thinning and geometry and total time and volume per hour

Thinning	Planting geometry, mxm	Cycle one		Cycle two		Cycle three		Total		*PMH*	m^3/PMH
		Time	Volume	Time	Volume	Time	Volume	Time	Volume		
First	2.7x2.7	144.78	18.86	101.02	11.89	NA	NA	245.80	30.75	4.1	7.51
	2.5x2.9	233.07	18.86	116.65	9.36	NA	NA	349.72	28.22	5.83	4.84
	2.4x3.0	137.5	18.86	88.97	9.64	NA	NA	226.47	28.5	3.77	7.55
	2.3x3.1	115.84	18.86	64.93	9.98	NA	NA	180.77	28.84	3.01	9.57
Second	2.7x2.7	85.11	18.86	107.22	16.84	NA	NA	192.33	35.7	3.21	11.14
	2.5x2.9	107.31	18.86	112.9	16.75	NA	NA	220.21	35.61	3.67	9.7
	2.4x3.0	97.94	18.86	81.67	17.34	NA	NA	179.61	36.2	2.99	12.09
	2.3x3.1	89.09	18.86	81.31	18.86	15.09	1.52	185.50	39.24	3.09	12.69

this. In other words, due to the individual tree volume being less in first thinnings, the multiple boom movements did not translate into a potentially higher volume harvested (Eliasson and Lageson 1999, Talbot et al. 2003). This phenomenon will potentially decrease productivity of the system in first thinnings (Belbo 2010).

Analysis of the scenario data revealed that the distance a harvester moved between harvesting stops and the volumes harvested at each stop influenced each other. In order to optimise machine working and movement time, a balance between these two factors would greatly increase the productivity. This is supported by results in other studies (Talbot et al. 2003).

When deciding on a feasible alternative to the control (2.5x2.9 m, 2.4x3.0 m and 2.3x3.1 m), the productivity results for the harvester were inconclusive in the first thinning mainly due to the great number of small trees. One would assume that the spacing geometries with the highest volume per harvesting stop, the shortest distance between stops and lowest total harvesting time consumption would appear to be the best alternative.

Harvester productivity decreased by between 1 and 3% in the first thinning and increased by between 7 and 8% in the second thinning. This was, however, a net increase in productivity over the two thinning operations. There was a general increase in productivity between geometries 2.4x3.0 m and 2.3x3.1 m when compared with the control. It is evident that these were the best suited alternatives to change planting geometry at this point.

5.3.2 Forwarder

Forwarder productivity depended on the distance travelled between loading points and the volume available at each stop in the scenario simulation (Table 11).

Table 11 Results of machine costing for first and second thinning for harvesting and forwarding operations (South African Rand)

Thinning	Planting geometry, mxm	Harvester cost, *R*/m^3	Forwarder cost, *R*/m^3	Total system cost, *R*/m^3
First	2.7x2.7	153.06	99.86	252.92
	2.5x2.9	154.81	154.95	306.76
	2.4x3.0	155.69	99.33	255.02
	2.3x3.1	158.41	78.37	236.78
Second	2.7x2.7	67.18	67.32	134.50
	2.5x2.9	62.58	77.32	139.90
	2.4x3.0	62.51	62.03	124.54
	2.3x3.1	62.08	59.10	121.18

The grapple size influences the number of times the boom had to be deployed. While boom movement influenced time consumed loading the forwarder, as with the harvester, travel time did not have a great effect on the productivity. The main influence of productivity, evident from this study, was the increase in forwarder productivity when volume per harvesting stop increased.

Similar travelling distances between harvesting stops were found in the simulation between the control, 2.4x3.0 m and 2.3x3.1 m, showing the importance of the volume per stop as a factor driving productivity increases. Overall productivity increases of between 21% (first thinning) and 12% (second thinning) could be achieved by using alternative planting geometries. Similar to that of the harvester, 2.4x3.0 m and 2.3x3.1 m were the most productive planting geometries for the forwarder.

5.4 Harvesting system cost

In general, there was a decrease in cost/m^3 between the control and the alternative planting geometries (Table 11). The planting geometries that led to the lowest costs were 2.4x3.0 m and 2.3x3.1 m in both first and second thinning operations. These two systems yielded an overall reduction in cost of 7% (*R* 16.14 m^{-3}) and 10% (*R* 13.32 m^{-3}) in first and second thinning, respectively. As discussed above, these two planting geometries did not significantly differ from each other in terms of volume per harvesting stop, distance between harvesting stop and time consumption per harvesting stop. However, a reduction of *R* 18.24 m^{-3} and *R* 3.66 m^{-3} could be achieved in first and second thinning operations, respectively, when choosing between 2.4x3.0 m and 2.3x3.1 m planting geometries; the latter having the lowest cost.

The results show evident financial benefit of adopting alternative planting geometries to the control one. However, by changing the planting geometry the potential cost reduction can make these thinnings more competitive for the current systems.

6. Conclusion

When optimising the planting geometries for mechanised thinning operations, it was found that the thinning simulator can effectively maintain stand regularity thus proving the efficacy of the method for the purpose of this study, and the overall system productivity could be increased by up to 8% and 21%, respectively, in harvester and forwarder productivity if the planting geometry was changed. This showed that rectangular geometries were superior to standard quadratic planting geometries, resulting in the possibility of achieving a cost reduction of up to 7% in first and 10% in second thinnings.

Adding to the understanding of stand characteristics, the development and application of a computer based harvesting simulation model has once again highlighted the power of simulation techniques in providing answers to these complex issues. Financial decisions to implement changes in stand management require the ability to test these scenarios without the associated risks involved by trial and error applications. This work has also attempted to change mindsets by exploring alternatives to standard, square planting geometries by showing that small adjustments can potentially improve overall harvesting productivity and costs and reduce damage to the stands.

The benefit of maintaining stand regularity in terms of tree growth characteristics and volume increment is evident. Furthermore, the objective of implementing other planting geometries, while maintaining stand regularity, has also shown to improve harvesting productivity and reduce overall harvesting system cost in a simulation environment.

Marrying the thinning and harvesting simulator with stand and tree distance dependent growth, simulators would provide scenario testing for the whole forestry value chain. This would ensure that parts of this unique value chain do not work in isolation, but provide detailed feedback throughout the system. This research has made a start at developing this interaction, where aspects of Operations Research are not seen in isolation but as a combined field for all forestry disciplines. Developing these links and interactions between silviculture, growth and yield and harvesting will benefit the forestry industry and increase its overall competitiveness.

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Benefits and challenges of shifting from manual approach to using optimization procedures in wood procurement planning

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Wood procurement planning is a challenge for the forest industry, particularly in natural forests where diverse raw materials can generate multiple products depending on mill configuration. Thus, developing plans to match supply with demand for final products is a complex problem. Optimization models can integrate factors in the planning process. In the literature, optimization models have been proposed, but few are actually used by companies. It is assumed that the complexity of the problem, and the expertise required limit their application. Nevertheless, such tools could improve profits for companies. The objectives of this study are (i) to quantify the gains associated with utilizing an optimization model in procurement planning, and (ii) to identify the challenges to adopt an optimization procedure in actual planning. An optimization software (LogiLab) is used to support this study. LogiLab maximizes profit through optimal allocation of raw materials to mills. The model simultaneously considers harvesting, transportation, forest heterogeneity, and mill performances. In contrast, manual planning approach by the company is focused on transportation distance. To compare both approaches we used a case study involving a Canadian forest company. The wood procurement planning process of the company was studied and compared with results obtained using the optimization approach. The optimized plan generated a higher profit due to a more efficient allocation. Results and actions needed for implementation are discussed.

Keywords: wood supply, wood allocation, forest planning, process implementation,

Introduction

Wood procurement planning in the context of natural forest is particularly challenging. Stands are diversified and characterized by variations. Matching specific stands or assortments to specific mill is difficult. Wood supply managers are expected to minimize procurement cost while meeting each mill's desired wood flow. While harvesting and hauling costs are always too high by wood purchaser, obtaining the assortments of logs best suited for a given production process is essential for global profits. The intensity of today's worldwide competition for forest products is amplifying the importance of developing systems for optimizing wood allocation (Coudé, 2010). While distance to mills is an easy factor to minimize, adding stand value for each specific mill in a large set of potential destinations is a complex task that makes planning much more difficult and time consuming. Several mathematical models have been developed and proposed to solve the forest to mills allocation problem. However, it appears that only few are actually being used by forest companies.

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Wood procurement planning must not only account for the four principal procurement activities that are: management, harvesting, roading and transport (Mosconi, 2014); it should explicitly consider milling operations and market demand fulfilment, usually with a profit maximization perspective. The contribution of optimization and simulation software for forest management purposes has a long history and has been largely documented (Paradis *et al*., 2013). The specific needs of mill supply planning and management has also been widely studied in the last decade (Table 1). Although most of these studies reported case studies with forest companies and presented significant gain achievable by optimization, empirical field observations indicate a limited usage of advanced optimization in enterprises. We could hypothesize that problem complexity, uncertainty levels and constant change in the natural and business environments, as well as the expertise required to use and adapt these models limit their applicability in an industrial setting. Nevertheless, the potential benefits warrant that further efforts be deployed to realize the efficiency gains that optimization can deliver. Few studies specifically consider implementation challenges when presenting optimization models.

Table 1. Wood supply elements considered by selected optimization models

Authors	Element considered in the model						Model benefit
	Forest management	Harvest operations	Road network	Transport	Transformation	Forest inventory	
Karlsson *et al.* (2004)	x	x	x	x			↓ Cost
Beaudoin *et al.* (2007)		x		x	x		↑ Profit
Marques *et al.* (2014)			x	x	x		↓ Waiting time
Gautam *et al.* (2014)	x	x				x	↑ Profit
Eyvindson and Kangas (2014)	x	x				x	↑ Profit
Morneau-Pereira *et al.* (2014)		x	x	x	x	x	↑ Profit

In the forest sector, wood supply planning is performed by managers using trial-and-error, simple heuristics, experience, and intuition (Morneau-Pereira *et al.*, 2014). Well documented software supported optimization approach for forest planning can be traced back to at least 30 years (Rönnqvist, 2003). However, the nature of the problems to be solved has continued to evolve and the expectations on planners have increased as a greater number of constraints must be considered (Rönnqvist, 2003). Therefore, using optimization in today's environment is believed to provide even more network efficiency gains for businesses.

The main objective of this study is to analyze the potential offered by mathematical optimization when allocating wood flows from a set of harvesting areas to a set of processing mills. Two sub-objectives are also associated with this broader goal: (i) clearly establish the benefits that a specific company could gain from using an existing simulation-optimization system that has been adapted for their specific context, in support of planning decision and (ii) evaluate the efforts and capabilities required to implement the proposed system.

Method

The methodological approach consists in comparing an actual wood supply plan, one prepared by forest planners following their business as usual method, with a plan deemed «optimal» from a mathematical programming approach. The «as-is» approach used by the industrial partner in this project has been described and analyzed step-by-step. It is, however, restricted to the operational plan that aims at selecting among a large set of possible harvest blocks which one to allocate to which mill. This is called annual programming (AP) by the company. Each step of the as-is process has been described in a general schematic (Figure 1).

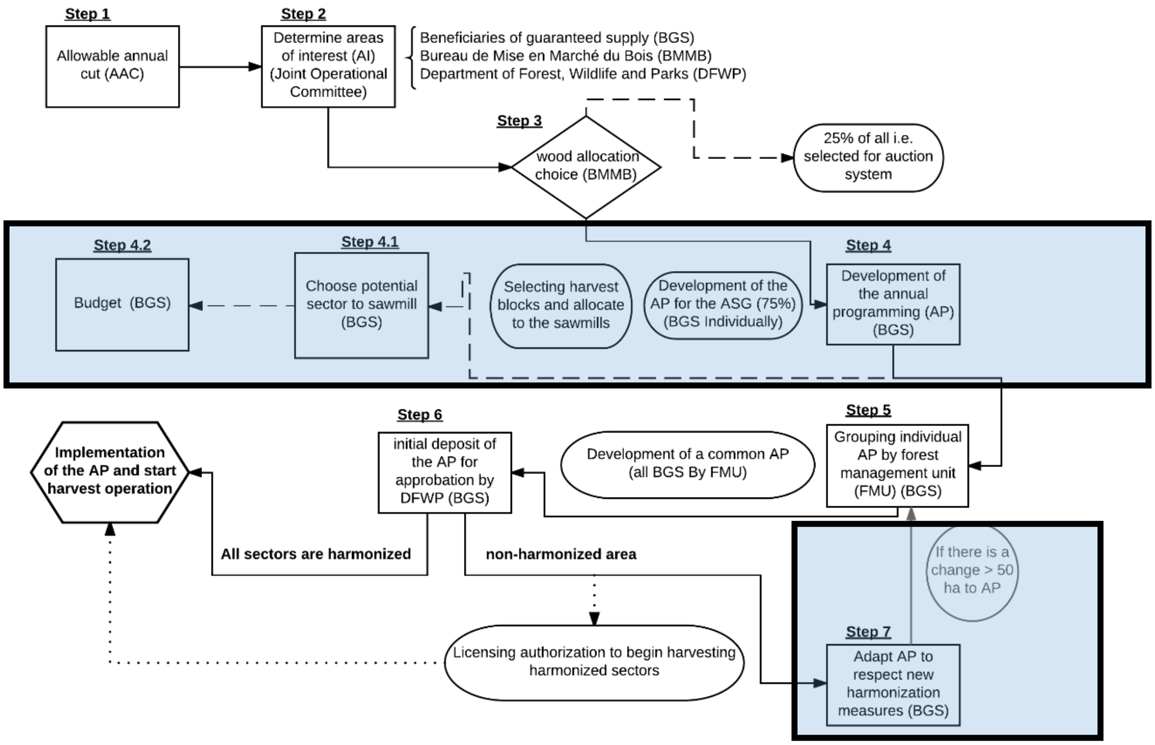

Figure 1. Current planning process used by industrial partner

In this figure, we can see in which steps of the planning process it is possible to intervene (mainly steps 4 and 7 as highlighted). Using this approach, it was possible to compare the optimized plan with a plan that was prepared manually. Both plans are prepared with similar information regarding future outcomes, i.e. the optimized plan does not benefit from perfect information.

Case study

The case study is based on the operations of a large integrated forest company operating several sawmills in Canada. A forest district supplying wood to five sawmills was selected to compare both approaches. These mills are mainly processing three forest species, and the supply mix is an important constraint to be accounted for at the mills. The forest district is subdivided in areas of interest (AI) that constitute the future harvest blocks. A well-developed road network is available ahead of block selection. Lumber sales are the main source of income for the network. Harvesting is performed by entrepreneurs using mostly cut-to-length machines but tree-length and combo systems are also available. Transport is carried out either by large payload truck (forest roads only) and regular four-axle forestry trucks. Only three mills (out of five) can receive wood by large trucks due to road restrictions. Harvesting teams divide logs or stems according to three possible assortments based on species.

Optimization model

The choice of an optimization model to be used for this study was based on two criteria, (i) ease of use and capacity to adapt it for the specific conditions of our case study (ii) elements of the supply systems that it accounts for. One of the challenges in implementing an optimization approach on a real industrial context is the constant changes in the forest sectors over the years. The model must therefore be easy to modify to be suitable. For those reasons we selected LogiLab, a web platform developed by the FORAC consortium to optimized wood flows in a network (Lemieux and Simoneau, 2014). LogiLab has been adapted to the allocation problem based on the work by Morneau-Pereira *et al.* (2014). The optimization model in LogiLab relies on linear programming to maximize value for the network. LogiLab allows the user to optimize and analyse their problem through a web-based interface. This characteristic could allow for a team of planners to work jointly and interactively on a plan from different locations. Our case study required several modifications to LogiLab's mathematical model and a Python file was used to directly modify the models without recoding in LogiLab. Results of the optimization can be viewed and shared through any generic web browser. However, detailed analyses including a greater level of detail are generally conducted using *.csv* files. Using comma separated files, we were able to develop and feed an Excel dashboard and compare the plans. The optimal plan was first generated and the results sent to the dashboard. Next, the "manual" plan forest to mill allocation was sent to the optimization model to evaluate the value of the as-is solution. Having both plans displayed in the same format made comparison possible.

LogiLab input parameters

Most inputs concerning forest operations were generated using FPInterface^{TM} a forest operations simulation software. Sawmills data were generated with Optitek^{TM} by simulating each stem and the resulting products with their associated values. FPInterface^{TM} and Optitek^{TM} are software developed by FPInnovations that are currently used by company of the case study. In the data set 67 harvest blocks were considered with three harvest modes. A +/-5% margin was allowed on systems proportion to provide a certain level of flexibility to the model but also respecting the contracts previously set with contractors. Other operational constraints from the planning team have been added to the model, for example a block having a total volume less than 12 000 m^3 could not be harvested tree-length. Each pile (sort) from a block could be transported to up to two different mills as long as it accounted for at least 8 000 m^3. Harvesting costs ($/$m^3$) account for the exact stumpage fee to be paid according to each tariff zone. The stumpage fees were obtained from the governmental chart of *Bureau de Mise en Marché du Bois* (BMMB) and were added in FPInterface^{TM}. Therefore, our system fully account for price difference based on wood quality.

LogiLab's input file includes each mill's minimum and maximum capacity. Minimum level corresponds to a level set by the company itself while a maximum level corresponds to values set in the licence agreement with the government. Transport constraints are set to reflect the road network's capacity per truck type. Transport costs ($/$m^3$) were generated using FPInterface^{TM}. They account for full cycle travel time, loading and unloading as well a possible fuel compensation set in a performance bonus system by the company. The full planning process using LogiLab is presented in figure 2.

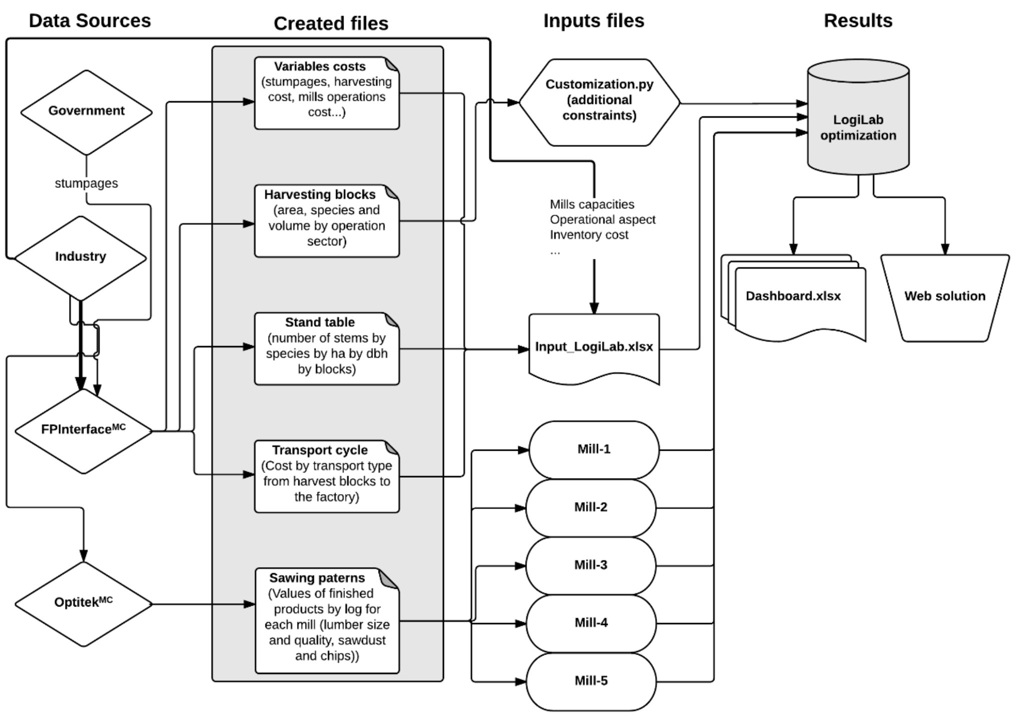

Figure 2. Planning process using LogiLab, FPInterface™ and Optitek™

Results

The proposed planning system combining LogiLab, FPInterface™ and Optitek™ as allowed to increase profit by 4.97% compared to the as-is approach used by the company (table 2). Globally, the optimization model finds opportunities to increase revenues and reduce production cost by allocating the right stem to the right mill. Lower revenues from chip deliveries are resulting from higher yield at the sawmill, this is perceived as a positive outcome.

Table 2. Comparison between LogiLab and manual plan

	Difference (LogiLab / Manual Planning
Global net value	+ 4.97%
Lumber benefit	+ 0.72%
Chips benefit	- 0.83%
Sawdust benefit	+ 1.82%
Production costs	- 0.04%
Transportation costs	- 3.58%
Harvesting costs	+ 1.01%

Detailed values for each mill are provided in Figure 3. Net benefits have increased for three out five mills in comparison with the manual planning approach (Mill-2, Mill-3, Mill-4) based on LogiLab's block allocation. The yield performance represented in Mpmp/M^3 has increased at Mill-2 and Mill-4 while the yield reduction at Mill-3 in the optimal scenario did not have a negative effect on the net value generated by that mill. A reduction in the volume processed at Mill-4 was observed, this decision did not negatively affect performance and revenues at that mill, confirming that with a good allocation the generated value can be higher.

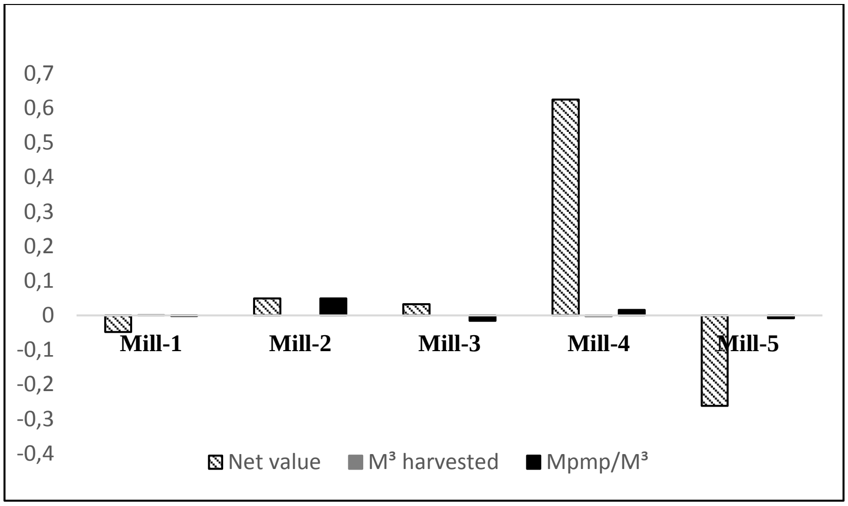

Figure 3. Difference between the optimized and as-is plans in regards to net value, harvested volume (in M^3) and yield performance (in Mpmp/M^3) for each mill

Our case study demonstrates the potential of a decision system that combines three previously existing software: LogiLab, FPInterface™ and Optitek™. This system can be operated by a group of professionals with college-level training (forest operations, wood science, process engineering…). At this time, a certain level of competency in computer programming is still required to adapt the optimisation module.

Conclusion

Optimization using LogiLab has allowed to increase profits generated by a network of sawmills receiving their logs from a shared set of harvesting blocks. Compared to the manual planning approach, benefits are attributed to improvements in the forest to mill wood allocation. Our case study involved a set of five sawmills of an integrated company for which real production and yield data was available. Detailed comparisons of the optimized and manual plans allowed proactive discussions among the planning team and the modellers. One very specific case of forest to mill allocation for given mill revealed decision based on historic conditions that needed to be revisited. Implementing our optimization planning system appears possible as long as initial training can be provided to support the use end-users. The main implementation challenge that we targeted so far are the skills required to change the mathematical model to allow companies to use optimization for themselves despite future changes. The three software used during the planning process of our experiment can yield benefits on their own, therefore if FPInterface™ and Optitek™ are not available, LogiLab can still be fed input data from other sources. The next steps in this research involve testing other scenarios and testing the impact of improved inventory data on decision making. We also intend to document the competencies required to operate and adapt the proposed planning system and the cost of each planning process.

Aknowledgements

The authors are grateful for the support provided by the industrial partner and FPInnovations involved with this project. Financial support provided by NSERC, FPInnovations and the FORAC research partners made this research possible.

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Are logging rates a driver of logging employment?

Shawn Baker[1] and Brooks Mendell[2]

Abstract

In this article, we examine available data on the logging industry and evaluate drivers of logging employment over the past thirty years. We focus on the relationship between logging rates, wood demand, and logging employment regionally and locally in the South. Southwide, annualized changes in logging employment have been closely tied to wood demand changes, while rate changes have more closely followed consumer inflation. Conventional wisdom that logging rates drive employment is not directly supported by the available data. Higher logging rates may affect the quality of the businesses serving the forest industry, but the number of businesses derives from wood demand. In the five post-recession years, logging rate growth outpaced inflation and wood demand recovered at a strong clip, yet employment grew minimally. This contrasts the employment drivers observed over the preceding 25 years, suggesting different logging industry behavior post-recession.

Keywords: wood procurement, logging capacity, wood demand

Introduction

Logging capacity is a concern for all wood-using facilities. If capacity is too low, mills can struggle to procure sufficient wood or may have to pay higher rates to attract suppliers. Previous research on logging capacity suggests that the southern US typically maintains an oversupply of logging capacity to ensure short-term wood shortages can be remedied by higher utilization of the existing capacity (Laestadius 1990, Greene 2004). Procurement organizations have two controls over wood suppliers in this scenario. They can control the volume of wood supplied (typically managed through weekly delivery quotas) and the price paid for wood (managed through spot and contract prices). A clearer understanding of the role each control has on changing logging capacity could help the entire industry. The common refrain for increasing logging capacity is that higher rates bring businesses back into the industry. If conventional wisdom holds, increases in logging rates within a market should correspond to employment increases.

The forest industry has changed significantly over the past 20 years with the divestment of company-owned lands from integrated companies and the rise of timberland owning and management specialists. The logging sector has not avoided these changes, as many firms work within wood dealer organizations, a significant number purchase stumpage to cut, and many directly contract cut and haul services with corporate owners/managers of timberland. The proportion of contractors directly contracting with mill procurement staff has likely declined, suggesting that the ability of wood-using mills to drive capacity changes might have changed. Demand from a willing consumer is still the *raison d'etre* of the logging industry, but the prevalence of middlemen may change the direct impact of efforts to influence capacity.

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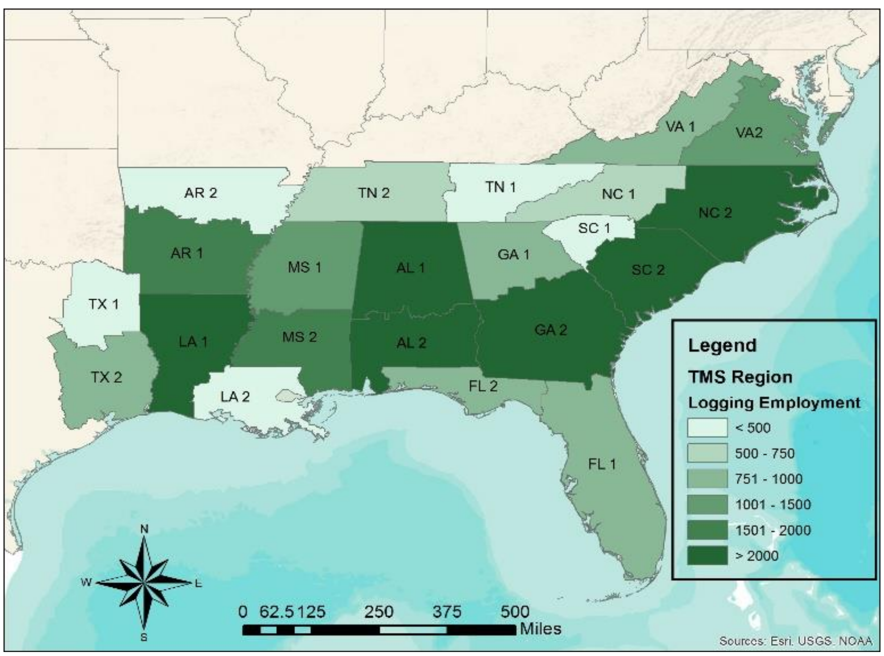
In this paper, we examine available data on the logging industry and evaluate drivers of logging employment over the past thirty years in the U.S. South, where additional data support a more detailed analysis relative to other U.S. regions. We examine four time periods: the last period of employment growth in the industry during the late 1980's and early 1990's, the period of moderate employment losses from the mid-1990's to the mid-2000's, the start of the recession from 2004 through 2009, and the recovery from the recession from 2009 through 2014. Our focus is on the relationship between logging rates, wood demand, and logging employment Southwide and in localized markets within the South.

Data and Methods

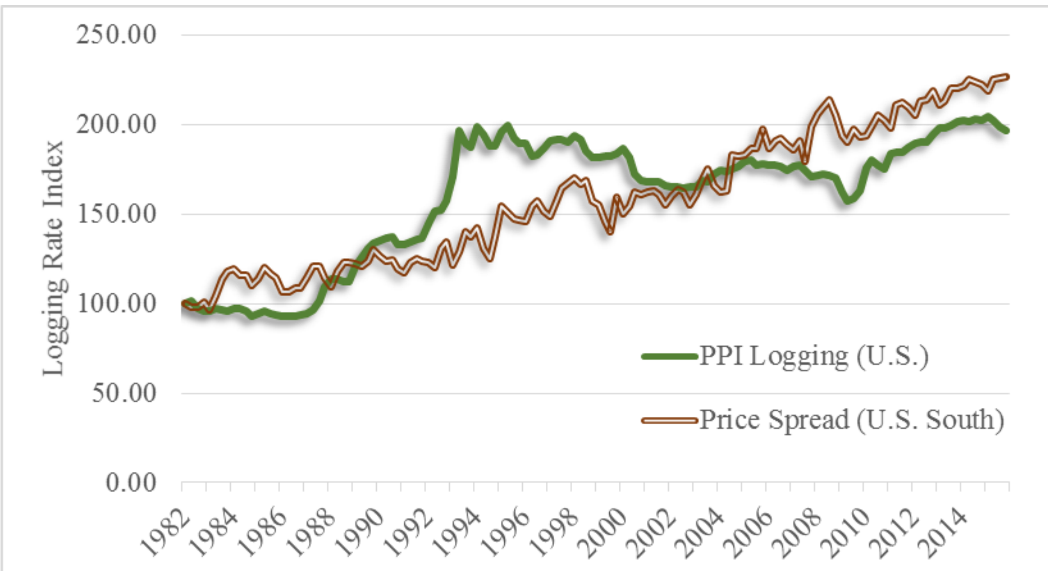
Data issues limit our ability to evaluate the logging industry. The Bureau of Labor Statistics (BLS) Quarterly Census of Employment and Wages tracks employment data in logging businesses at the county level. We aggregated this county-level data for the South into 22 separate districts, corresponding to Timber Mart-South's 22 half-state regions (Figure 1). We converted quarterly employment values into annual averages. State-level employment data are available into the 1980's, but detailed, county-level estimates were aggregated from 2004 through 2014.



Source: Bureau of Labor Statistics

Figure 1. Current Employment in the Logging Industry by Timber Mart-South Region

Data on logging rates is not publicly available for most U.S. regions. BLS reports a Producer Price Index (PPI) for Logging, which provides a national measure of changes in logging rates (Figure 2). The PPI Logging started in December 1981 with a value of 100. It provides a measure of inflation in prices paid to logging contractors for their services over time. Data on localized logging rates is difficult to track. Timber Mart-South reports logging rates for the South as a whole; however, for this analysis, we wanted to isolate rate changes within a wood market. To estimate these changes, we used the spread between delivered and stumpage prices for a basket of wood products in the region. This spread may comprise a number of costs (procurement costs, dealer fees, etc.), but the major component should be cut and haul. This estimate provides a proxy at the local level given the available data. We combined the spread of three wood products in a weighted average to estimate the logging cost of businesses in the region (Figure). The pine pulpwood spread represented 50% of the final value, the pine sawtimber spread represented 30%, and pine chip-n-saw represented the remaining 20%. We focus on pine products for consistency; however, it also made tracking changes in the spread for areas without pine as the predominant species potentially misleading. As a result, Tennessee, Western Virginia, and Western North Carolina were excluded, leaving 18 total markets.



Sources: Bureau of Labor Statistics, Timber Mart-South
Note: “Price Spread” proxies logging rates in the South and is the difference in Southwide stumpage and delivered prices for a basket of pine products, derived from Timber Mart-South data. It is indexed to a value of 100 in 1st quarter of 1982 for comparison against PPI Logging.

Figure 2. Estimated Logging Rates in the U.S. and U.S. South, 1982-2015

The total volume of wood harvested, a measure of demand for logging services, also informs our examination of logging employment. Since loggers are paid per delivered ton, their total revenue combines the rate received and amount of wood delivered. Demand data from the U.S. Forest Service Timber Product Output Database are available at the county level for some years (typically alternating years). We aggregated county level data for the 18 markets for all years available after 2004, which resulted in four measurement years: 2005, 2007, 2009, and 2011. In addition, Southwide wood demand data were available from the U.S. Forest Service for previous years, and were compared against rate and employment trends at the regional level prior to 2004.

We regressed changes in logging employment between years in which TPO data were available at the county level (2005, 2007, 2009, and 2011) within each of the 18 markets against a number of variables to test the significance of each with logging employment. Values were differenced to minimize the impact of time-related trends. We tested the change in demand for all pine products within each market by summing the TPO data at the county level for each reported year and subtracting from the previously reported year. Logging rate changes were tested by comparing the change in the annual average spread between stumpage and delivered prices in the report years. The spread in prices was measured in real terms by correcting for inflation using the Consumer Price Index. Finally, we examined the data for differences in patterns between report years using a dummy variable for the 2007-2009 period and the 2009-2011 period.

Results

Southwide, annualized changes in logging employment followed wood demand changes, while rate changes tracked consumer inflation until the recession (Table 1). The conventional wisdom that logging rates influence employment is more nuanced. Changes in our logging rate proxy do not correlate with changes in logging employment levels. Of note, the post-recession recovery period defied previous patterns. In the late 90's and early 2000's, decreasing demand, combined with rate increases lower than inflation, exacerbated employment losses beyond changes in demand. The opposite effect has not been apparent in the most recent period. Rate growth materially outpaced inflation (diesel is the likely culprit) and wood demand recovered at a strong clip; but this yielded negligible employment growth.

Table 1. Annualized change in forest industry and economic measures in the U.S. South

Period	Logging Employment	Stumpage-Delivered Price Spread	Wood Demand	Consumer Price Index
1986-1995	1.78%	3.76%	1.61%	3.73%
1995-2004	-2.36%	1.58%	-0.42%	2.41%
2004-2009	-4.70%	2.31%	-4.68%	2.58%
2009-2014	0.01%	2.90%	2.21%*	1.99%

Sources: Bureau of Labor Statistics, U.S. Forest Service, Timber Mart-South, Forisk
* U.S. Forest Service data not yet available, estimated by Forisk Consulting.

Regression results within the 18 wood markets largely agree with longer term region-wide trends in the data (Table 2). First, they verify that wood demand is the strongest predictor of changes in logging employment. Wood demand accounted for 41% of the data variability. Second, the dummy variable for 2011 indicates that the most recent employment data differ in their relationship to wood demand. In fact, the slope associated with wood demand in the 2011 data is essentially zero (4.38 – 4.80) after accounting for standard errors of the estimates. In other words, changes in logging employment post-recession were not tied to wood demand. The dummy variable testing differences between earlier periods were not significant. The third key trend relates to logging rates. Inflation-adjusted logging rates do not offer predictive value relating to logging employment. There is a marginal influence between rates and demand. An increase in logging rate increases the rate at which additional wood demand increases logging employment. Specifically, if rates increase $1 per ton, a 100,000-ton increase in wood demand in a region should increase employment by 5.3 employees, instead of 4.4 at lower logging rates.

Table 2. Regression coefficients (and standard errors) on logging employment in the US South from 2005 through 2011.

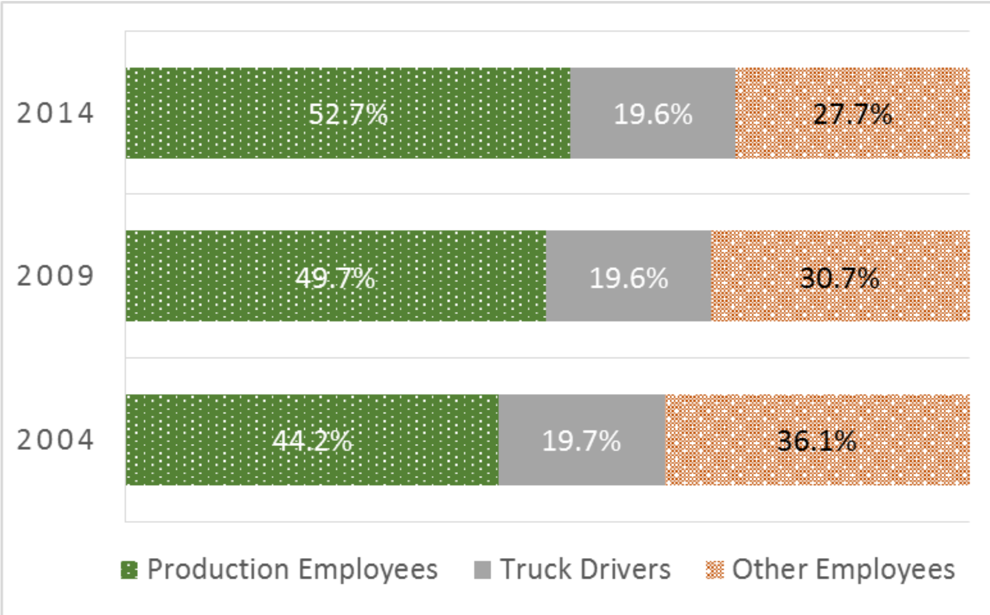
Variable	A	B	C	D	E
Intercept	-71.30 (14.33)***	-98.82 (19.90)***	-86.28 (19.85)***	-92.04 (21.19)***	-83.43 (21.57)***
Wood Demand (10^5 tons)	4.39 (0.67)***	3.61 (0.77)***	4.38 (0.80)***	4.20 (0.84)***	4.37 (8.30)***
Year – 2011 (dummy)		60.69 (31.20)*	67.01 (30.11)**	78.35 (33.39)**	63.70 (34.17)*
Demand*Year			-4.80 (2.02)**	-4.82 (2.02)**	-4.99 (2.00)**
Logging Rate				5.71 (7.16)	2.31 (8.65)
Demand*Logging Rate					0.93 (0.58)*
Adjusted R-squared	0.414	0.441	0.484	0.480	0.495
F-statistic	42.75***	24.29***	19.41***	14.62***	12.55***

P-values: *** < 0.01, ** < 0.05, * < 0.1

Discussion

The results raise a number of questions that this study is not able to directly answer. The lack of any correlation between logging rate changes and logging employment is one of the most important. On a local level, "other" sources of income may muddy the waters. Some companies might buy and market their own timber. Success or failure in the stumpage markets would be as great a determinant of success as cut and haul rates. Side projects such as road construction and maintenance could also make the difference between surviving or not. Individual markets might have supportive machine financing opportunities, unique labor competition, or local weather sensitivity that our data are not suited to identify. The last five years also differed from other periods in that employment wasn't consistently increasing or decreasing. Increases occurred in the last two years. Analysis in the future might clarify the drivers between 2012 and 2017.

A second possibility is that the logging industry restructured during the recession. Companies may have strategically managed their labor to lower costs while maintaining capacity. The data used in this study examines all logging employees. Not all employees actually cut and deliver wood to mills. Employees classified as a "logging equipment operator" or a "timber faller" had different employment trends from non-production employees (Figure 3). Between 2004 and 2009, woods-workers shrank 6% and by an additional 1% between 2009 and 2014. Logging companies trimmed non-production employees at a greater rate. "Production" employees in logging businesses represented 44% of the total employment in 2004 and had increased to 53% in 2014. This may have minimized the impacts to total production capacity.



Source: Bureau of Labor Statistics

Figure 3. Distribution of U.S. Logging Industry Employees by Occupation

Data that allows us to look into trends in localized markets have somewhat surprising results. In the recession, the spread between stumpage and delivered prices increased at roughly the pace of inflation, while demand declined rapidly. Marginal revenue for the industry as a whole declined and businesses closed. As we've recovered, the spread increased faster than inflation, and demand has increased. Estimates of wood demand indicate that the aggregate timber harvest is higher now than in 2009. If true, we should see higher marginal revenues for the sector fueling growth in employment. To date, we have not seen growth commensurate with the indicators.

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Follow that tractor: What truck-mounted GPS tells us about log truck performance

Shawn Baker[1], Roger Lowe III[2], and Dale Greene[3]

Abstract

The increasing prevalence of GPS in log trucks offers the opportunity to identify areas for improvement in trucking operations. We analyzed four months of data from GPS units mounted on nine logging trucks operating in the coastal plain of the Southeast US to increase our understanding of current log truck performance. We processed over 90,000 individual location records representing 762 driver-days. Trucks averaged 48% loaded miles over the course of the study and delivered 2.2 loads per day, though there were a significant proportion of days on which no loads were delivered. Number of loads delivered in a day did not correlate with increased percent loaded miles. Waiting time in the woods exceeded waiting time at the mill earlier in the day, while mill wait times were generally greater after 10AM. Unloaded miles to and from home represented between 10 and 30% of total miles driven, depending on the driver. Further analysis of truck GPS data can provide metrics to benchmark truck performance and identify driver training opportunities.

Keywords: loaded miles, turn time, delays

Introduction

Trucking is a vital link in the wood-supply chain, but it also represents a significant source of operating cost. Improvements in trucking efficiency can lower costs and improve the competitiveness of the industry. In the past, efficiency gains as a result of increasing scale of log truck operations have not been captured due to the structure of the logging and forest industries. Recent efforts to consolidate trucking operations offer the possibility of applying improvements to the logistics of hauling operations. Prior to a more detailed investigation into either of these approaches, a better understanding of the current state of knowledge is needed.

Deckard et al. (2003) provided a comprehensive analysis of turn time at receiving facilities. They found that the best facilities had average turn-time of 20.5 minutes while the average turn time of the rest of the mills sampled was 32.5 minutes. In addition, Deckard (2001) reported that mill turn times were highest at 5 and 6 AM for all mills. Few U.S. studies have examined the woods turn time. Dowling (2010) found that median woods turn time was 60 minutes for four logging crews in Virginia, while median mill turn time was 25 minutes. McCormack (1990) reported daily percent loaded miles varied between 33% and 51% for one week on a southeastern US logging operation.

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This project is an effort to assess the current state of trucking operations through an analysis of GPS data from haul trucks in Florida between January and April 2015. The data are presented to highlight key issues of interest, including percent loaded miles, load delivery times, waiting/idle times, and travel speed.

Methods

A trucking company operating in southern Georgia and northern Florida provided four months of data from truck-mounted GPS units in ten logging trucks. The company currently uses a truck dispatcher to route trucks throughout the day, which differs from the typical log trucking operations in the U.S. South (McDonald et al. 2001). The GPS data included roughly 96,000 unique GPS locations. The GPS receiver on one of these trucks malfunctioned for the entire period, leaving us with effectively nine trucks (two other trucks had periods of malfunction covering a few days as well). GPS data were processed over the course of each day for each truck (a driver-day). Removing the data from days on which trucks were not operated, we were left with 762 driver-days of information.

Using ArcGIS, we identified mill and forest sites, offices, homes and other general points of interest to aid in the subsequent analysis. Every recorded GPS point was classified as office, mill, woods, home, gas, food, repairs (third party mechanic), or roads. Lacking specific data on loads delivered, we estimated the loaded and unloaded portions of travel based on travel from harvest sites to mill sites. Trucks were classified "loaded" when traveling to a mill location after stopping at a forested site either immediately prior or in the previous afternoon. Travel to a mill location while loaded was deemed a load delivered, while visits to mill sites while unloaded were not counted in the total loads delivered (Figure 1). Multiple visits to forest sites without a visit to a mill site posed a processing challenge. These trips likely represented equipment movement between harvest sites, but much of this mileage was classified as "loaded" based on the information we had available. The final stop of a given day was used to determine if the truck was loaded or empty at the end of the day (if the final stop was a mill location or a forest site). The first and last trips of the day were coded separately to determine the impact of travel to and from home on overall truck performance.

GPS receivers recorded a location every five minutes while the truck was operating, so there is an uncertainty of ± 5 minutes on all times reported below. The data recorders also stored the rate of speed which was based on an internal measure of distance traveled over that time interval. We estimated the distance traveled by multiplying the rate of speed times the interval between subsequent points. Idle times at various locations were tallied as subsequent recorded points with speeds less than 10 mph. The length of time between GPS points increased the likelihood that movement at a given location (driving onto or out of a loading site, moving under an unloading crane, etc.) would be recorded with a positive speed. A 10 mph threshold was selected as it eliminated instances of multiple movements within a given location (which would artificially increase the number of "stops" at that location).

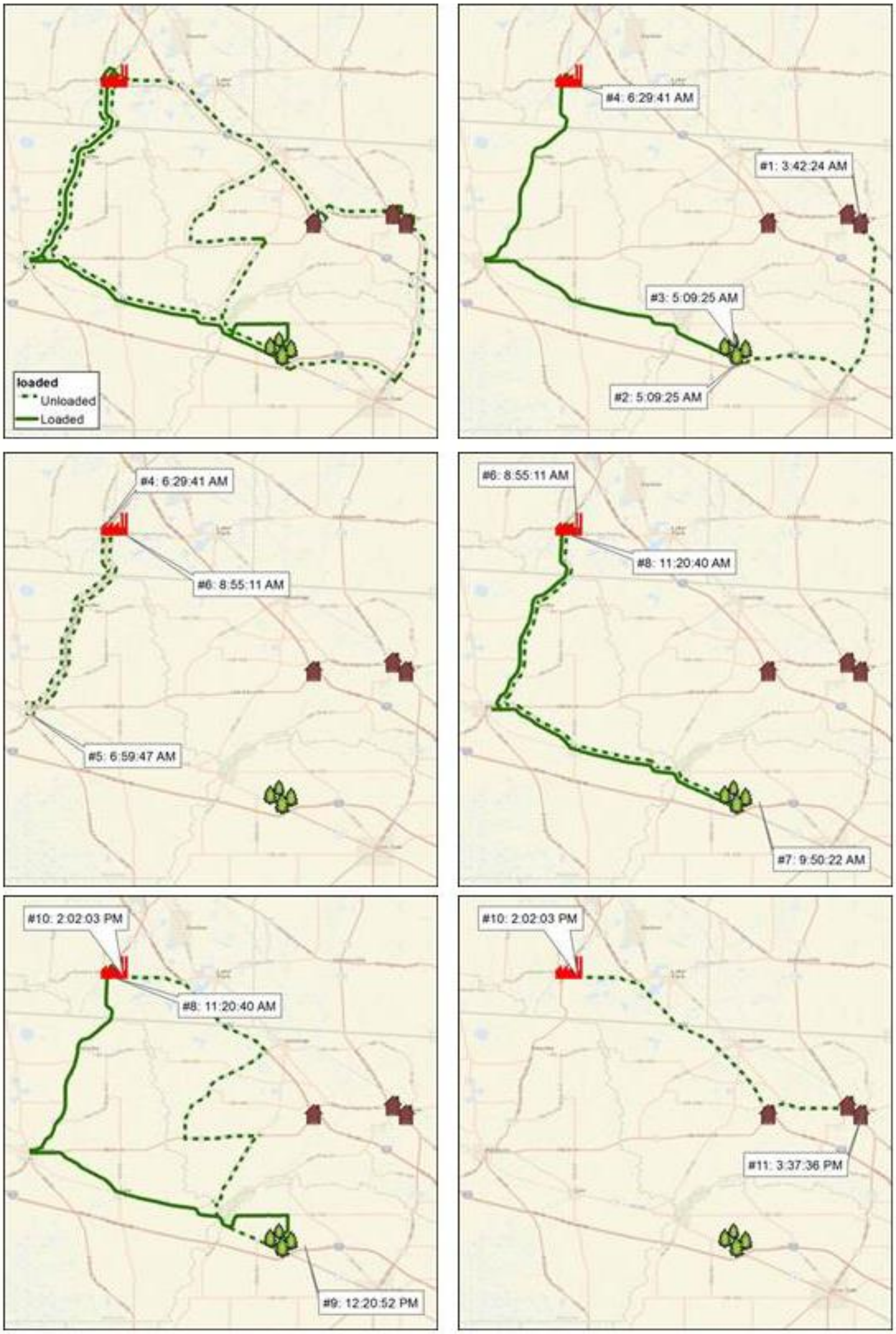

Figure 1. Sample processed data for a given day, with three loads delivered over 12 hours.

Results

Trucks averaged 2.2 loads delivered per day. This average was certainly lowered by the number of days on which no loads were delivered. Trucks drove significantly more miles on days where they delivered two or more loads, than on days where they delivered one or fewer (Figure 2). On days in which two or more loads were delivered, however, the average mileage driven did not vary significantly, typically within 10 miles more or less of 350.

The majority of loads were delivered between 10 AM and 2 PM (Figure 3). The number of deliveries declined consistently from this peak both later and earlier throughout the day, with the exception of a second, smaller spike in deliveries at 5 AM.

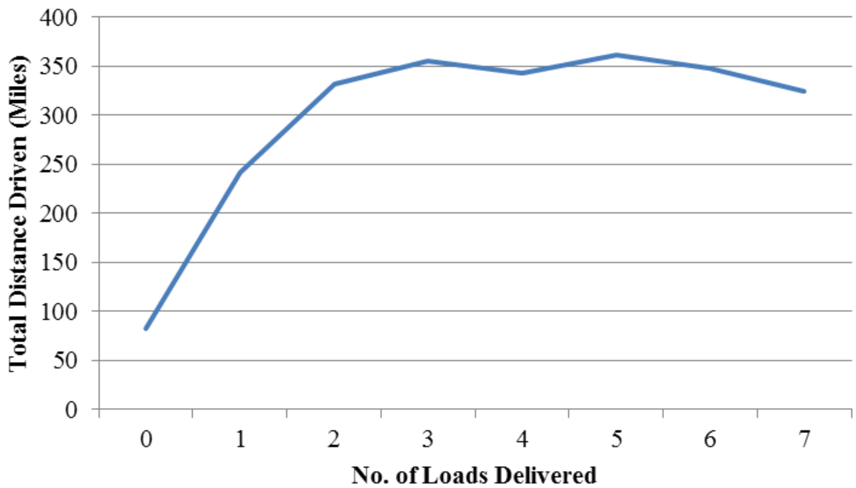

Figure 2. Average daily mileage driven by number of loads delivered.

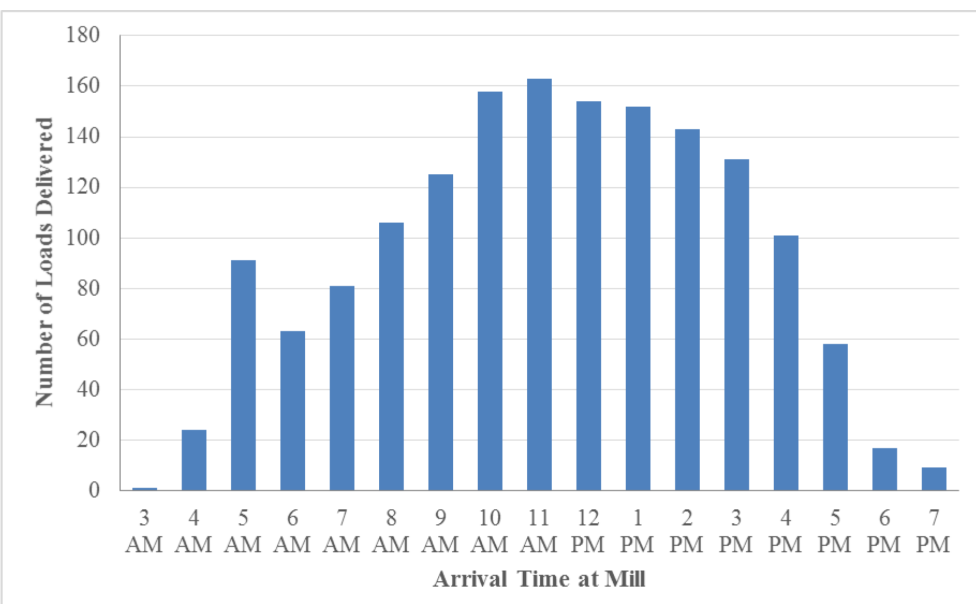

Figure 3. Total loads delivered to mill facilities by the hour of arrival.

The nine trucks averaged 47.7% loaded miles. Two trucks averaged over 50% loaded, however, the analysis was confounded slightly by time spent moving equipment between jobs. Analyzing the data after the fact, it was difficult to determine when a truck was moving equipment rather than just relocating. The two trucks with the highest percent loaded miles may have had their percentages artificially inflated by periods of moving equipment. Number of loads delivered in a day was not correlated with higher percent loaded miles (Figure 4). The impact of moving between jobs can be seen most clearly when examining the percent loaded miles on days with no delivered loads.

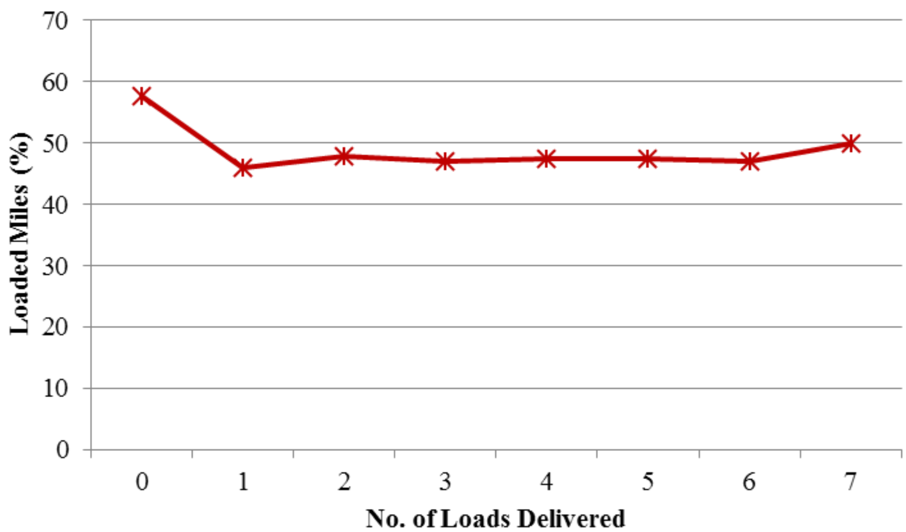

Figure 4. Percent loaded miles based and daily number of loads delivered.

Trucks were not always empty when traveling to and from home, some drivers would occasionally take a load home and deliver it early in the morning. Empty trips home occurred on roughly 77% of the days recorded. Empty miles driven at the start and end of the day represented between 10 and 30% of the total miles driven.

On average, all trucks spent more time waiting in the forest than at mill sites. Time spent at mill sites and forest sites differed significantly in their impacts on total production. At four loads delivered per day, the average time spent in the woods approached the average time spent in the mill (Table 1). At lower production levels, however, the average turnaround time in the woods was significantly higher than time at the mill. Out of 1,678 individual trips to the forest, 118 (7%) were for trips lasting greater than 2 hours. Out of 1,717 trips to the mill, only 15 (1%) lasted greater than 2 hours. The mean trip time was impacted by the larger number of trips to the forest which lasted over two hours. Mean time spent in the woods per trip was 45 minutes compared to 32 minutes spent at the mill. The median time spent in the forest per trip was 30 minutes compared to 25 minutes for trips to the mill.

The average time spent at a mill site per delivery typically ranged between 20 and 40 minutes, with longer stops typically corresponding to fewer total daily loads. Time spent in the forest, however, increased substantially as the number of loads delivered declined (Figure 5).

Table 1. Time spent per trip waiting at mill sites and in woods separated by number of loads delivered per day.

No. Loads	**Time At Mill (min./trip)**			**Time In Woods (min./trip)**		
	Mean	*C.V. (%)*	*N*	*Mean*	*C.V. (%)*	*N*
0				34.3	143.3	37
1	37.9	91.9	140	83.6	88.2	122
2	37.9	73.0	570	54.7	91.0	579
3	29.2	56.4	639	39.4	83.2	602
4	28.3	53.4	244	35.3	79.1	225
5	25.3	37.1	105	34.1	73.2	98
6	19.6	48.0	12	26.5	44.5	10
7	20.1	38.2	7	25.7	33.7	6
		Total:	1717		Total:	1679

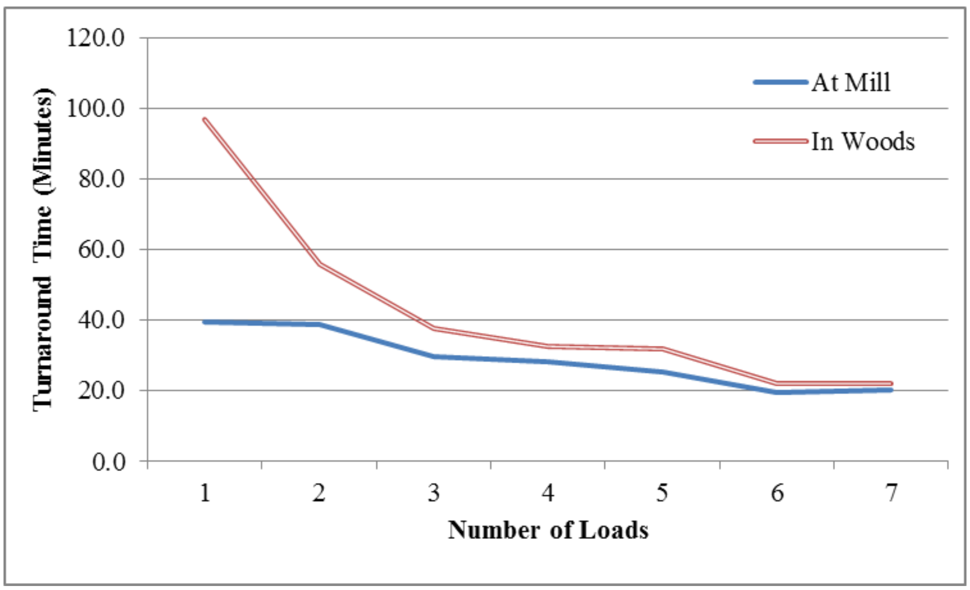

Figure 5. Average turnaround time at mill and woods sites by number of loads delivered.

The distribution of waiting time throughout the day provides a clear indication that the early morning presents the greatest probability of longer wait times (Figure 6). Woods wait times decline throughout the day, with the exception of trips that occur in the 5 PM hour. Mill wait times decline in the afternoon, but are fairly constant in the morning after 7 AM. The substantially longer wait times in the morning could be a source of concern based on the relative spike in the number of deliveries at 5 AM noted earlier (Figure 5). Woods wait times must be observed with a modicum of caution as many trips to the woods did not necessarily coincide with obtaining a load of wood. We estimated 1,668 loads were delivered by all trucks during the duration of this study. In the wait time data, we have 1,715 individual trips to mill sites (this is a fairly close level of concurrence), while 2,561 unique trips were recorded to woods sites. These may have resulted from a number of possibilities, but equipment movement would register as two forest site visits per trip without an actual load being received. These excess trips likely cloud the actual loading time distribution throughout the day.

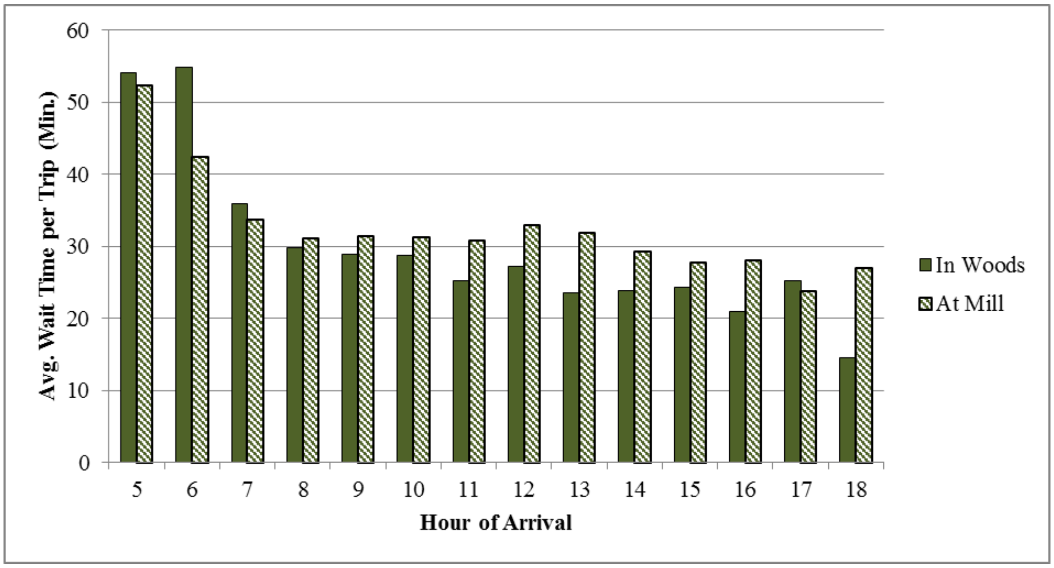

Figure 6. Average wait time in the woods and at mill sites based on the hour of arrival of individual trips.

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Impact of bucking automation on productivity and log specifications compliance rate

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Abstract

Today's cut-to-length harvester include built-in capabilities to automate the bucking process. The objective of this research was to investigate if using a higher degree of automation in the bucking process would systematically increase harvesting productivity and log specifications compliance rate.

Three degree of automation have been investigated and compared: manual, semi-automatic and automatic. In all, 5 experienced operators were involved in separate case studies. A randomized complete block experimental design was implemented north-west of Lac-St-Jean in Quebec, Canada. The experiment took place from January to August 2015. Contrasts analysis with one-way ANOVA were performed at the 5% level of statistical significance. Also, a series of semi-structured interviews was conducted with each operator.

Greater automation of the bucking process did not systematically increase productivity nor log specifications compliance rate. One operator had a significantly higher productivity under full automation, but this difference seems to relate to work technique rather than automation itself. Two operators had significant differences in log specifications compliance rate for length measurement. In these cases, results showed a decrease in log specifications compliance rate associated with full automation of the bucking process. Interestingly, results also indicate that each degree of automation seems better suited to specific operating conditions (operator's work technique, tree and stand characteristics). Further work is needed to identify these conditions.

Keywords: Harvester, harvesting head, on-board computer

Introduction

There is a limited amount of previous work which quantifies the impact of log processing automation on productivity and log specifications compliance rate or quality. Brander et al. (2004) report on a project looking into automating some of the knuckleboom functions on a harvester. An experienced harvester operator ran a simulator in a conventional mode to set a productivity benchmark. Students achieved a productivity level of only 25% of that of the experienced operator. However, the student's productivity level increased to 80% of that of the

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experienced operator when the automated functions were enabled. Unfortunately, the research team did not investigate if the automated functions could increase the productivity level of the experienced operator.

In mechanized harvesting, the human factor is now considered a productivity bottleneck (Löfgren and Wikander, 2009 ; Hellström et al, 2009). This is explained by a stressful work environment where an operator must activate close to 2,000 functions per productive machine hour (Löfgren and Wikander, 2009; Hellström et al., 2009).

Several studies also focused on log merchandizing. For example, Murphy et al. (2004) investigated adaptive control of bucking on harvesters to meet order book constraints. Marshall et al. (2006A) tested three mathematical models for bucking-to-order. Other researches focused on measurement precision and value loss such as in Corneau and Fournier (2005), Marshall et al. (2006B).

To our knowledge, no investigation have been conducted to determine if automation of the bucking process could help in increasing productivity and the quality of products.

This research aimed to answer the following questions:

(1) Does the degree of automation of the bucking process affect the mechanized log processing productivity (m^3/PMH)?
(2) Does the degree of automation of the bucking process affect the log specifications compliance rate (%)?

Materials and Methods

A field study was conducted from January to August 2015 to collect data on the impact of different degree of automation of the bucking process.

Two harvesting crews participated in the study. Crew "A" had two operators and crew "B" had three operators (Table 1). None of the operators alternated day and night shift.

Table 1: Harvesting crews and operator-shift allocation

Crew	Operator ID	Shift
B	1B	Day
	2B	Day
	3B	Night
A	4A	Day
	5A	Night

Three degree of automation were tested: Manual (M), Semi-automated (S), and Automated (A). In the M mode the operator activates the saw for all the logs. In the S mode the operator activates the saw only for the first log and the remaining of the stem is processed without human intervention. Finally, in the A mode, the operator only press on the tree species button and the whole stem is processed without human intervention.

A randomized complete block experimental design was implemented to control external factors related to site and stand characteristics. All operators were treated as individual test case since the research team was informed but had no control as to where the crews would harvest. Nevertheless, it was possible to measure and record data for different degrees of automation in all blocks. Experimental units within each block, correspond to a two-hour operation for a given degree of automation.

Site and stand characteristics

The field study was carried out in 9 operating sectors north-west of Lac-St-Jean in Quebec, Canada. Stands were natural black spruce (*Picea mariana*) and were over 100 years of age at the time of harvest. Data was gathered in over fifty blocks. Table 2 provides a summary of the averages and ranges of stand characteristics for the main operating sectors.

Table 2: Stand attributes for the main operating sectors

	Sector 1	Sector 2	Sector 3	Sector 4
Average Breast Height Diameter (mm)	162 (143 – 187)	204 (174 – 218)	159 (149 – 172)	134 (124 – 151)
Piece size (m^3/stem)	0.158 (0.111 – 0.259)	0.287 (0.202 – 0.322)	0.199 (0.134 – 0.297)	0.089 (0.068 – 0.124)
Stocking (stems/ha)	729 (433 – 1089)	546 (489 – 615)	1145 (919 – 1385)	1249 (1027 – 1414)
Volume (m^3/ha)	112 (65 – 213)	157 (107 – 187)	230 (142 – 365)	107 (88 – 127)

Manual measurements

Manual measurements were taken to determine the actual length and diameters of the logs. For every logs, length, small-end diameter and large-end diameter were measured. A loggers tape and diameter tape were used for length and diameter measurements. Measurements were taken over-bark for both the harvesting heads and the manual measurements.

Harvesting heads

Table 3 provides information on the three harvesting head used in this research. All harvesting head were calibrated weekly.

Table 3: Harvesting head characteristics

Crew	B	A	
Brand	Log Max	Ponsse	Ponsse
Model	7000 XT	H7	H7
Carrier	TigerCat H855C	Timbco 445	Landrich HC-310
Software	Log Mate 500	Opti4G	Opti4G
Software version	1.05.0020	7.10	7.15
Caliper	Haglöfs 1.5	Ponsse Caliper +	Ponsse Caliper +
Measuring tape	Ruban Digitech Tape	Standard	Standard

Productivity measurement

On the Ponsse heads, productivity data were acquired through the Opti4G software. Two measuring device were used for the Log Max head. Volumes were computed by the Log Mate 500 software, while the number of productive machine hours were collected with a FPDat. Tests were conducted in the summer of 2014 to calibrate the time measuring device and module to properly evaluate the number of productive machine hours.

Log specifications compliance rate

The compliance rate was evaluated for two criteria: (1) percent of logs ± 5 cm of target length, and (2) percent of logs respecting topping rule. The topping rule for the last log requires a small end diameter less than 9.1cm, otherwise the log is deemed too short. That last log must be at least 6 feet long otherwise it is left in the forest.

Statistical analysis

Contrasts analysis with one-way ANOVA were performed at the 5% level of statistical significance. Table 4 presents the planned contrasts which correspond with the current degree of automation used by each operator against the fully automated mode. The GLM Procedure in the SAS statistical software was used to perform the analysis for each operator. The homogeneity of variances and the normality of residuals were checked.

Table 4: Contrast to realize for the operators

Operator	Contrast
1B, 2B, 3B, 4A	M vs A
5A	S vs A

Results

Productivity

Descriptive statistics gathered for the productivity comparisons are presented in Table 5. Results of analysis of variance for the five operators are reported in Table 6. Data from operator 4A were transformed.

Table 5: Descriptive statistics for productivity comparisons

Operator	**Number of samples**	**Transfo.**	**Average productivity (m^3/PMH)**	**Standard error (m^3/PMH)**
1B	15		23.3	3.5
2B	7		36.0	3.2
3B	15		18.9	2.2
4A	5	Logarithm	31.9	3.8
5A	8		21.1	1.3

Table 6: Results of contrasts for the productivity criterion for each operator

Operator	**Contrast**	**D.F.**	**S.C**	**M.Quad.**	**F**	**Prob > F**
1B	M vs A	1	2.080	2.080	0.170	0.684
2B	M vs A	1	0.183	0.183	0.020	0.898
3B	M vs A	1	5.376	5.376	1.090	0.314
4A	M vs A	1	0.576	0.576	0.040	0.853
5A	**S vs A**	**1**	**15.016**	**15.016**	**9.140**	**0.019**

There were no statistically significant differences between degrees of automation except for operator 5A. We recorded higher productivity under the fully automated mode for that operator in all of his blocks with minimal, maximal and average difference of 0.2 m^3/PMH, 5 m^3/PMH and 1.94 m^3/PMH respectively. A semi-structured interview with the operator related the observed difference to his work technique rather than automation itself. The operator said to prefer "taking his time to deck the wood properly for the forwarder". Global team productivity was his objective.

Log specifications compliance rate

Log Length within 5 cm of target length

Descriptive statistics gathered for the compliance rate of log length comparisons are presented in Table 7. Results of analysis of variance for four operators are reported in Table 8. Operator 2B did not participate in this experiment. Data from operator 4A were transformed.

Table 7: Descriptive statistics for log length compliance rate comparisons

Operator	Number of samples	Transfo.	Avg compliance rate (%)	Standard error (%)
1B	7		92.12	3.466
3B	7	Reciprocal	93.15	3.393
4A	6		95.76	1.936
5A	5		95.48	2.935

Table 8: Results of contrasts for the log length compliance rate criterion for each operator

Operator	Contrast	D.L.	S.C	M. Quad.	F	Prob > F
1B	M vs A	1	2.326	2.326	0.190	0.673
3B	**M vs A**	**1**	**1.03E+08**	**1.03E+08**	**6.980**	**0.038**
4A	**M vs A**	**1**	**27.301**	**27.301**	**7.280**	**0.043**
5A	S vs A	1	5.476	5.476	0.640	0.470

There were statistically significant differences between degrees of automation for operators 3B and 4A. No degree of automation provided systematically higher compliance rate under this criterion. Meanwhile, the manual mode provided higher compliance rate in 5 samples out of 7 for operator 3B and in 5 samples out of 6 for operator 4A. The differences in compliance rate ranged between 1.1 - 9.1%, and 1.0 – 5.8% for operators 3B and 4A.

Respect of topping rule

Descriptive statistics gathered for the compliance rate of log topping rule comparisons are presented in Table 9. Results of analysis of variance for four operators are reported in Table 10. Operator 2B did not participate in this experiment. Data from operator 1B were transformed.

Table 9: Descriptive statistics for the topping rule compliance rate comparisons

Operator	Number of samples	Transfo.	Avg. Compliance rate (%)	Standard error (%)
1B	7	Reciprocal	84.18	8.611
3B	7		86.33	11.696
4A	4		92.01	11.497
5A	5		86.62	7.732

Table 10: Results of contrasts for the topping rule compliance rate criterion for each operator

Operator	Contrast	D.L.	S.C	M.Quad.	F	Prob > F
1B	M vs A	1	0,047	0,047	2,770	0,140
3B	M vs A	1	248,643	248,643	1,820	0,226
4A	M vs A	1	0,032	0,032	2,390	0,220
5A	S vs A	1	0,013	0,013	2,190	0,213

There were no statistically significant differences between degrees of automation for all operators under this criterion.

Discussion

According to our results, none of the three degrees of automation systematically provides higher or lower productivity nor log specifications compliance rate. Meanwhile, a closer look at the data may indicate the influence of external factors such as trees, stands and terrain characteristics. For example, operator 3B reached average productivities of 19.3 m^3/PMH (S.D.=4.9) and 18.4 m^3/PMH (S.D.=4.6) for the manual and automated modes respectively. There was no statistically significant difference in productivity. We measured higher productivity in the automated mode in 4 samples out of 15. For these 4 samples, minimal, maximal and average differences in productivities were 0.1 m^3/PMH, 7.5 m^3/PMH, and 2.6 m^3/PMH. In the other 11 samples, the productivities in the automated mode were lower than those for the manual mode. For those 11 samples, minimal, maximal and average differences in productivities were 0.1 m^3/PMH, 7.4 m^3/PMH, and 2.1 m^3/PMH. Similar results can be observed for all the operator except for operator 5A who had statistically significant differences that could be explained by his work method.

Further analyses are required to identify in which conditions a given degree of automation provides higher productivity. Having the ability to adapt the degree of automation according to the encountered conditions would be of interest since in our context an increase of 1 m^3/PMH throughout the year translates into close to C$ 80,000 for the owner of the harvester.

Conclusion

The objective of this research was to investigate if using a higher degree of automation in the bucking process would systematically increase harvesting productivity and log specifications compliance rate.

Greater automation of the bucking process did not systematically increase productivity nor log specifications compliance rate. One operator had a significantly higher productivity under full automation, but this difference seems to relate to work technique rather than automation itself. Two operators had significant differences in log specifications compliance rate for length measurement. In these cases, results showed a decrease in log specifications compliance rate associated with full automation of the bucking process. Interestingly, results also indicate that each degree of automation seems better suited to specific operating conditions (operator, tree and stand characteristics). Further work is needed to identify these conditions. The benefits provided to operators through a work load reduction as automatic modes are adopted would also deserve further attention.

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Timber Procurement Practices in Wisconsin: Responding to Seasonal Variation in Timber Availability

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Abstract

Recent research has found significant seasonal variation in timber availability in Wisconsin, with fewer than half of all timber sales available for harvest April-July. This creates a challenge for mills that need a consistent supply of wood throughout the year. We conducted a survey of Wisconsin mills to document their timber procurement practices and analyze their response to seasonal timber harvesting restrictions. Fifty-five mills representing 7.5 million tons of wood consumption responded, which yielded an adjusted response rate of 40% and represented approximately 75% of annual statewide wood consumption. The average procurement radius ranged from 75 miles for small sawmills to 124 miles for pulpmills. Peak inventory levels exceeded 30 days for each quarter of the year. Mills increased inventories during the first quarter, reduced inventories in the second quarter when spring road weight restrictions were in effect, and inventories remained relatively stable during the third and fourth quarters. The vast majority of timber was purchased as roundwood in short lengths (i.e. 100 inch pulp sticks and logs <16 ft). Gatewood was the largest source of wood for all mill types, although small sawmills reported purchasing nearly one-third of their volume directly from landowners. Seventy percent of respondents had adjusted their procurement practices as a result of seasonal timber harvesting restrictions with increased delivered prices, increased inventory levels, and increased use of satellite wood yards the most common changes. Seasonal restrictions motivated by oak wilt, seasonal weight limits on public roads, and access/transportation issues were reported to be most impactful.

Keywords: Timber harvesting restrictions, Fiber supply

Introduction

Wisconsin produces more paper than any other state in the U.S. (Wisconsin Department of Natural Resources [WDNR] 2016b) and ranked 18th in timber harvest volume in 2011 (Oswalt et al. 2014). The forest products industry is critical to Wisconsin's economy as its second largest manufacturer and employer of over 60,000 people (WDNR 2015). Currently, growth on

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Wisconsin's 17.1 million acres exceeds harvest by 95% (Perry 2015), meaning that the forests could contribute to an expanded forest industry.

Wood fiber is the largest component of direct manufacturing costs in the forest products industry (Siry et al. 2006), making it critical for Wisconsin mills to purchase wood at a competitive cost. Unfortunately, the delivered cost of pulpwood in Wisconsin has been among the highest and most volatile in the U.S., according to recent research (Gibeault et al. 2015).

Recent research found that fewer than half of all Wisconsin timber sales were available for harvest between mid-March and mid-July as a result of seasonal timber harvesting restrictions (Demchik et al. 2016). For example, many public roads have significantly reduced weight limits during spring break-up that preclude transportation of timber from the forest to the mill (Wisconsin Department of Transportation 2016), stands with at least 15 ft^2ac^{-1} of oak basal area should not be harvested between early to mid-April and mid-July to prevent spread of oak wilt (WDNR 2016a), and many sales may only be harvested when the ground is frozen or dry to prevent soil and hydrological disturbance (Demchik et al. 2016). Seasonal timber shortages can result in temporary price increases (Todd and Rice 2005), and therefore mills may choose to increase inventories prior to the onset of restrictions. However, this strategy requires significant storage space and results in capital invested in raw material being unproductive for significant periods each year (Lang and Mendell 2012).

Because the forest products industry is a critical component of the state's economy and sustainably produced wood fiber is essential for its continued vitality, it is important to understand how Wisconsin mills purchase raw material and the impact of seasonal restrictions on their operations. Therefore, the objectives of this study were to document timber procurement practices in Wisconsin and assess the impact of seasonal restrictions on Wisconsin mills.

Methods

We conducted a mail survey of 165 Wisconsin mills during the fall of 2015 using the Dillman (2007) Tailored Design Method. All mills received an invitation letter, a cover letter and questionnaire, and a reminder postcard. Non-respondents also received a second cover letter and questionnaire. We addressed correspondence to each mill's procurement forester, or the mill manager if a procurement forester could not be identified. For companies that owned multiple mills, but purchased timber as a single entity, that organization was counted as a single entity. Respondents were asked to describe their procurement practices within the past 12 months, although some questions asked about general practices and others asked about ten year trends.

The questionnaire was eight pages long and consisted of 38 questions that collected information about species of timber purchased, production level, timber procurement practices, and seasonal timber harvesting restrictions. To facilitate data analysis, mills were placed in the following categories based on their responses: small sawmills, large sawmills, and pulpmills. Small sawmills purchased less than 50,000 tons of wood per year, while large sawmills purchased 50,000+ tons of wood per year. Pulpmills included paper mills and composite mills (e.g. OSB).

Because of the small sample size for the survey, we compared responses between mill types using the Kruskal-Wallis test and the Dunn-Bonferroni post-hoc procedure. We calculated a confidence interval for the mean response to 5-point Likert scale question to determine whether the response was different from neutral. If the confidence interval did not overlap with the neutral response ($\bar{x}$ = 3), that response was reported as significantly different from neutral. We applied a finite population correction factor when calculating confidence intervals for each mill type (Scheaffer et al. 2006). We estimated that there were 15 pulpmills, 130 small sawmills, and 17 large sawmills in the state. All statistical analysis was conducted at the $\alpha = 0.05$ level using SPSS (IBM Corp. 2012).

Results and Discussion

Twenty-three mills were removed from the sample because the survey was undeliverable, the facility had closed, or the mill did not purchase its own timber. Sixty-three questionnaires were returned, of which 57 contained usable data, resulting in an adjusted response rate of 40%. Respondents reported annual wood consumption of approximately 7.5 million tons, which represents approximately three-quarters of the annual timber harvest in Wisconsin (Perry 2015). Therefore, many nonresponding mills were probably closed or were small, hobby-type mills.

Procurement Practices

Most timber in Wisconsin is purchased as roundwood in short lengths. Of course, all raw material purchased by sawmills was in roundwood form. Seventy-two percent of this material was in lengths shorter than 16 ft, 15% was 16-32 ft, and a similar percentage was purchased as 100-inch bolts. Pulpmills purchased 74% of their timber as roundwood, 18% as clean chips, with the remainder composed of whole tree chips and sawmill residuals. All roundwood pulpwood was purchased in 100-inch lengths. The reliance on shortwood is somewhat unique to Wisconsin, and is probably a remnant of past practices, extensive use of cut-to-length logging equipment, and use of the Scribner log rule, which penalizes long log lengths.

The average timber procurement radius was 75 miles for small sawmills, but extended to 124 miles for pulpmills (Table 1). High transportation costs have previously been cited as contributing to high delivered costs in Wisconsin (Gibeault et al. 2015).

Gatewood purchased from loggers was the primary source of timber for all types of mills (Figure 1). Gatewood has been the primary source of pulpmills' wood fiber for at least thirty years and its prevalence has increased over this period (Stier et al. 1986). Small sawmills purchased nearly one-third of their timber directly from forest landowners. Not surprisingly, very little timber volume was sourced from fee land, including none for pulpmills.

Table 1: Procurement radius for sawmills and pulpmills in Wisconsin. Procurement radius was defined as the distance within which the organization purchased 90% of its timber.

Mill type	Average procurement radius (miles)	Standard error	Min	Max
Large sawmill	106	11	40	300
Small sawmill	75	6	10	200
Pulpmill	124	11	75	250

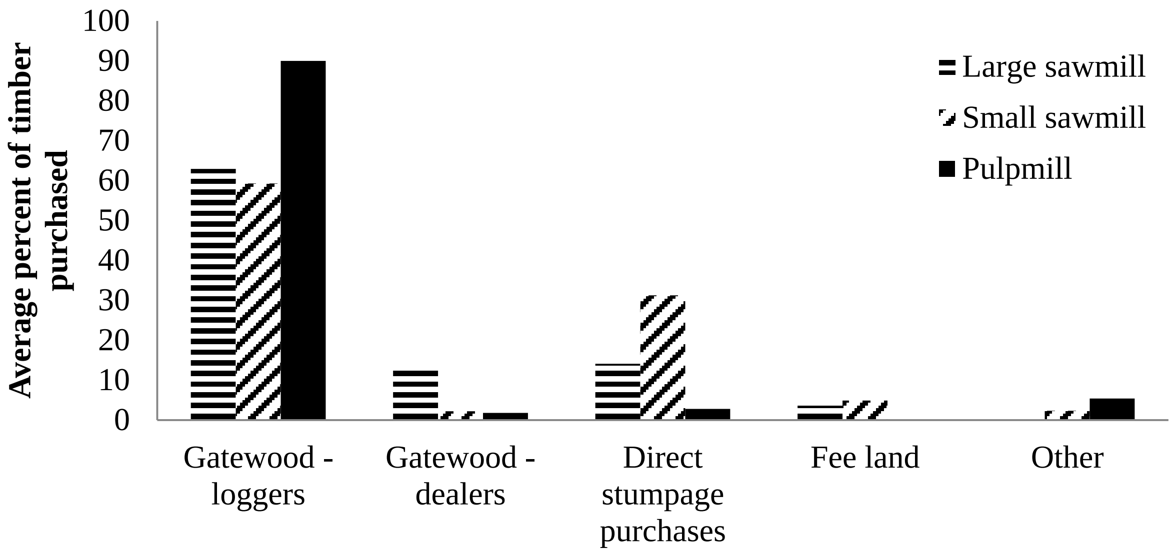

Figure 1: Sources of roundwood and chips for large sawmills, small sawmills, and pulpmills in Wisconsin.

Procurement staffs averaged 2, 3, and 4.5 people per firm for large sawmills, small sawmills, and pulpmills, respectively. The majority of large sawmills and pulpmills did not purchase timber directly from forest landowners, while 72% of small sawmills employed at least one person that purchased timber directly from landowners. For each mill type, the most common source of direct stumpage was family forest landowners. Pulpmills rated increasing the amount of timber on the market as the most important motivator for making direct stumpage purchases, while reducing delivered wood cost was the most important motivator for small sawmills. Large sawmills rated additional control over timber supply and overcoming seasonal restrictions as the most important motivators for pursuing this strategy.

Mills generally built up inventory during the first quarter of the year, reduced inventory during the second quarter, and maintained lower inventories during the third and fourth quarters (Figure 2). A similar pattern was reported by many pulpmills in Maine (Todd and Rice 2005). Because of limited timber availability during the second quarter resulting from spring break-up road weight restrictions, oak wilt restrictions, and soil and hydrological restrictions, mills generally increased inventories prior to the onset of these restrictions. Seasonal timber harvesting restrictions was the most important factor that influenced inventory levels for pulpmills, while weather was most important for sawmills. Inventory levels have remained remarkably similar over the past thirty years when a 2-3 month supply was the norm (Stier et al. 1986). Nonetheless, these inventory levels are higher than Wisconsin's competitors in the northeastern and southern regions of the U.S. Gibeault et al. (2015) cited seasonally high inventory levels as contributing to high delivered pulpwood prices.

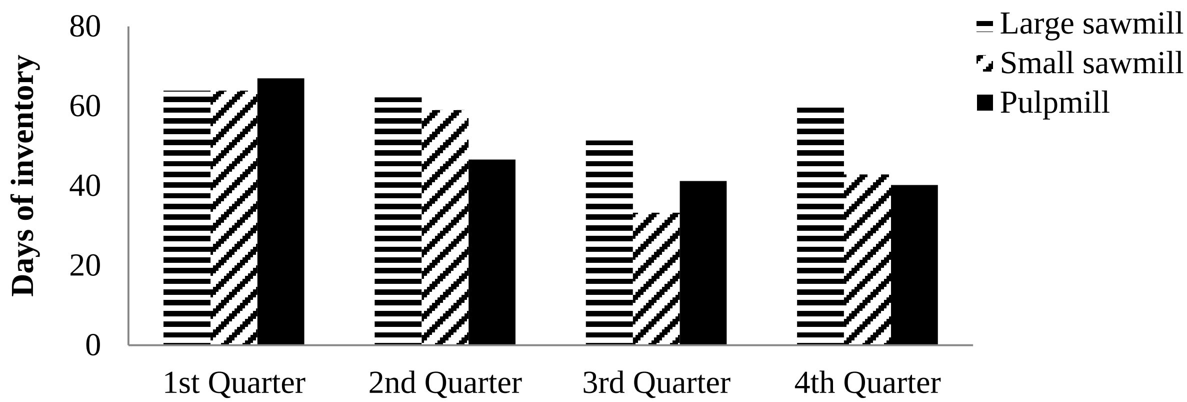

Figure 2: Peak inventory levels for large sawmills, small sawmills, and pulpmills in Wisconsin during the four quarters of the year.

Response to Seasonal Restrictions

Seventy percent of respondents had altered their timber procurement practices because of seasonal timber harvesting restrictions. All pulpmills reported changing their practices as a result of restrictions. The most common changes included increased delivered prices when restrictions are in effect, increased inventory levels, and increased use of satellite wood yards. There was a significant amount of variation in response to seasonal restrictions. This was expected because seasonal restrictions will impact each firm differently based on the mill's species mix, production level, location, and existing procurement strategy. For example, oak wilt restrictions would be expected to have minimal impact on pine mills, but a sizable impact on hardwood sawmills.

Respondents reported significant costs associated with seasonal timber harvesting restrictions. The largest cost components were increased inventory levels, satellite wood yards, and reduced wood quality during extended storage (Table 2). In total, pulpmills reported $2.7 million annual costs associated with seasonal timber harvesting restrictions. More than half of small sawmills reported production cutbacks as a result of seasonal restrictions. Generally, small sawmills reported the highest costs relative to their scale of operations, which may be attributed, at least in part, to the value of their raw material. Respondents rated access/transportation, oak wilt, and seasonal weight limits on public roads as having the greatest negative impact on their operations. This is logical because each of these restrictions impact large acreages and/or is in effect for a significant portion of the year.

The vast majority of respondents did not consider these restrictions to be cost-effective (Table 3). Mills again reported that these restrictions made them less competitive. This supports findings of previous research indicating that two-thirds of timber sales in Wisconsin include at least one seasonal timber harvesting restriction (Demchik et al. 2016) and that Wisconsin's delivered pulpwood prices are higher than its competitors (Gibeault et al. 2015).

Table 2: Mean cost of seasonal timber harvesting restrictions to forest products industry mills in Wisconsin. Cost per ton was calculated as the reported cost by a firm divided by that firm's annual wood consumption.

Type of cost	Mill type	Mean cost ($)	$/ton	% Reporting cost
Increased inventory	Small sawmill	$84,167	$3.25	39
	Pulpmill	$1,671,250	$3.55	100
Satellite wood yards and increased transportation costs	Small sawmill	$9,444	$0.48	22
	Pulpmill	$706,250	$1.11	88
Reduced wood quality from extended storage	Small sawmill	$49,444	$4.14	44
	Pulpmill	$111,875	$0.15	50
Down-time or reduced production	Small sawmill	$45,833	$2.46	50
	Pulpmill	$0	$0	0
Total costs[1]	Small sawmill	$188,888	$10.33	
	Pulpmill	$2,651,875	$4.93	

[1]Includes costs not displayed in the table.

Table 3: Forest industry representatives' views of seasonal timber harvesting restrictions as currently applied.

Seasonal timber harvesting restrictions, as currently applied are or have:	Mill type	% Agree	% Disagree	Mean response (1 = strongly disagree, 5 = strongly agree)
A cost-effective method of protecting the environment.	Large sawmill	0	50	2.30[*A]
	Small sawmill	29	42	2.74[A]
	Pulpmill	0	89	1.70[*A]
Increased the cost of delivered wood to this mill.	Large sawmill	50	20	3.60[*AB]
	Small sawmill	69	13	3.66[*A]
	Pulpmill	100	0	4.70[*B]
Beneficial to Wisconsin's forest industry.	Large sawmill	0	50	2.40[*A]
	Small sawmill	25	50	2.66[A]
	Pulpmill	10	70	2.10[*A]
Make Wisconsin's forest industry less competitive in the marketplace.	Large sawmill	40	10	3.50[*AB]
	Small sawmill	47	19	3.44[*A]
	Pulpmill	90	0	4.50[*B]

[*]Mean response was statistically different from neutral ($\bar{x}$ = 3, α =0.05).
[A,B]Responses connected by the same letter are not statistically different using the Kruskal-Wallis test.

Conclusion

This study documented challenges to Wisconsin's wood supply chain. Mills face long hauling distances as a result of current mill locations in relation to the forest resource. Mills generally purchase short log lengths, which increases handling costs at the mill and in the woods. In addition, mills are forced to maintain high inventory levels to accommodate seasonal timber shortages resulting from seasonal timber harvesting restrictions and spring thaw forest conditions. Mills reported significant costs resulting from seasonal timber harvesting restrictions (Table 2). Most of these costs were associated with inventory levels, satellite wood yards, and reductions in timber quality rather than higher prices paid to suppliers.

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Utilization of Phone Application Technology to Record Log Truck Movements in the Southeastern U.S.

Marissa "Jo" Daniel[1], Tom Gallagher[2], Tim McDonald[3]

Abstract:
Delays incurred by loggers hauling wood from the landing to the mill affect profitability and have the potential to make harvesting some areas unfeasible. Past studies were conducted to determine delay time a driver may have at the mill but very little research has been conducted analyzing the drivers wait time at the landing or the cause of delays a driver may encounter while driving from one location to another. In order to accurately gather information concerning delay times at the mill, the landing and during travel to and from each location a phone app was created that recorded driver location using GPS as well as an alert which allowed the driver to comment and record reasoning for a delay after the truck has moved less than 1500 feet in approximately 15 minutes. The app provided multiple reasons for the delay which created a user-friendly program requiring a minimal amount of time. By directly asking the driver the reason for the delay at the exact moment it is occurring, we were able to gather accurate information in real time regarding delays and therefore better able to deduce economic efficiency. This project was funded through W.S.R.I. (Wood Supply Research Institute). Preliminary research was conducted in the state of Alabama, Ohio and South Carolina with intentions of expanding it to other portions of the United States.

Keywords: delays, android phone, google technology, WSRI

Introduction:
Delays incurred by loggers hauling wood from the landing to the mill affect profitability and have the potential to make harvesting some areas unfeasible. Studies have been conducted to determine round trip turn times for logging trucks from the landing to the mill, however these studies failed to portray real life situations such as traffic accidents, road conditions, lunch breaks, admin delays and waiting to load that can potentially cause delays and influence overall harvest cost (Deckard, Newbold, and Vidrine 2003, Holzleitner et al. 2011, Barrett 2001, Sankaran & Wood 2007). These past studies collected delay response data using fleet management equipment that connected to the individuals' tractor but unless there was someone monitoring the computer screen observing all of these delays for the duration of the driver's work day, delay reasons were not recorded. Logging companies are looking for ways to reduce their overall and haul costs and if that company is forced to hire someone to observe truck locations and inquire about delays, they will not be reducing their costs significantly enough. By directly asking the driver the reason for the delay at the exact moment it occurred from a piece of equipment he has with him at all times anyway, accurate information in real time is recorded regarding haul costs and therefore better able to deduce economic efficiency.

Potential harvest sites are discarded after an economic analysis is conducted because of the haul costs associated with the sale. Haul costs produce one of the biggest expenses to the logger a majority of the time due to increased fuel prices and frequent maintenance costs to maintain equipment that travels in a variety of road conditions (Mathews 1942). Even the best drivers and businesses inevitably incur delays and although trucks that are idling due to a delay use less fuel than those that are driving on the road, they are losing production time and therefore losing money (Fluck 2012). These delays may be in the form of maintenance, breakdowns on either the tractor trailer or another piece of equipment which pauses the entire logging system process, waiting in line at the mill to unload because of a mill regulated quota, lunch breaks, administrative delays, or even dealing with traffic during travel (Baumgras 1978). Although it is understood that delays will occur, the types of delay, the duration of the delay and where the delay is occurring represent information that if communicated quickly could be used to diminish delay times or at least analyze them more accurately when determining haul costs.

Weintraub et al. 1996 found that decreasing log truck delays decreased workers hours and the number of men needed for hauling due to its increase in efficiency and productivity for Chilean companies. Carson 1989 stated that hauling costs were up to half of logging costs associated with southern forestry in the United States and even when conducting operations such as thinning the haul costs were still approximately 20-30%. Although there are factors which loggers must acknowledge are fixed costs (fuel prices, maintenance repairs, labor and insurance fees), haul costs due to delays are not one of them. Murphy 2003 and McDonald et al 2001 stated that truck drivers typically have thousands of potential roads they can travel to reach the mills and if owners are not planning truckers hauling routes or sharing trucks between companies this lack of preparation could lead to expensive delays and inefficiencies. Ways to decrease delays within hauling costs have been reasearched in the past, however, none of the delays were completely erased nor were they determined if the delay they were resolving was the paramount issue. Our study will identify the most significant delays in the United States with regard to hauling logs.

Objectives:

1) Create a phone app that recognized when the logging truck moved less than 500 meters in 15 minutes. This app then contacted the driver and inquired about the delay providing multiple reasons for the driver to choose. This could inadvertently allow owners to ensure that their workers are as efficient and productive as possible and increase overall profitability.
2) Analyze the most frequent reasons for the log truck to be delayed and decide if there are options to remediate.
3) Compare results across the nation to conclude if delays are similar throughout the logging industry.
4) Produce a more accurate economic analysis to determine if hauling delays are affecting the overall profitability potential for the timber harvest.

Justification:

The study was conducted using a cell phone app because cell phones now play such an immense part of everyone’s lives regardless of age or gender. A recent survey indicated that 92% of adults in the United States own a cell phone and that 68% of these adults own a smartphone (Monica Anderson 2015). This number has increased 33% from 2011. Due to this fact, our belief was that more accurate results could be collected in real time from loggers using their cell phone as the medium rather than if you would try and inquire at the end of the week or even the end of every day on paper. Initially there was a thought to have loggers record delays manually in a delay record book since truck drivers are required by law to keep log books recording their drive miles and hours, however these are also not always kept up to date and therefore it was assumed since the log books required by law are not always accurate and up to date ours may not be well maintained either. Bird et al. (2003) found that delays are not significant to the truck driver, therefore, the individuals incur a mentality of why should they remember exact details. With a thought process such as this, the use of any recording device that isn't in time becomes null. Our cell phone app alerted the driver with a sound and vibration similar to that of a text message. The driver selected the multiple choice response related to the delay and the icon disappeared so there was no need for the driver to select any further buttons. By utilizing a common tool, that most drivers are familiar with, we expected to see delay data recorded from the initiation of the program with minimal learning curve associated with using the program.

The study chose to record round trip delays from the landing to the mill rather than one-way delays for two reasons. First, one-way trips have already been covered in previous studies (Holzleitner et al. 2011, Barrett 2001, Sankaran & Wood 2007). These studies did a good job of portraying delays as they occurred one way but in order to be able to truly fix the delay issue it needs to be understood exactly where, when, and why the delays are occurring. This project intended to inquire about delays throughout the entire day and therefore every segment of the trip the driver covers to determine why the delay is occurring. The second reason for the round trip study was based on the fact that if the phone app was downloaded onto the drivers' phone, it was not able to differentiate between the drivers' routes to the mill or to the landing. Rather than create more confusion and potential errors by having the driver turn the app on and off for each trip, it was better to simply leave the app running and gather data the entire day.

This study was conducted with the overall goal of calculating a more accurate haul cost analysis for drivers. Originally introduced by Mathews (1942), but still found to be true today, haul costs are one of the most expensive aspects of logging due to the elevated fuel costs, the distance required to haul the wood to the mill, and the maintenance costs incurred from traveling over road conditions which range from muddy/dirt/rocky roads to paved interstate highways. If haul costs become precise then the logger may find that harvest sites previously deemed non-profitable due to high-cost estimation are potentially possible. This study has the potential to save the logger money by highlighting lag time areas the driver, the mill and/or logger need to improve on, thereby saving everyone money.

Approach

Development of the phone application was initiated in the spring of 2015. The app was a google based application which only ran through Android-based phones; I-phones were not programmable for this project due to their high clearance security settings. The trucking app was programmed using Java. The phone application was shared to designated participants through a Gmail/Google drive account that was created specifically for each driver for this project. All collected data was received and stored in the driver's google drive account and was then shared through google drive so that it could be analyzed. Python was chosen to convert files to a KML file so that data may be viewed in google earth to better analyze drivers routes and delays.

Initial data collection began in the spring of 2016 and has intentions of continuing through the summer of 2017. Logging companies from the states of Alabama, Ohio and South Carolina were used for the initial research. These states were chosen based on accessibility of companies and their willingness to participate in research studies. Further state inclusion will depend on initial analysis findings but has the potential to expand throughout the United States to any logging company associated with W.S.R. I. (Wood Supply Research Institute). Logging companies from states outside our knowledge base will be contacted via major universities and W.S.R.I. affiliation in the respective regions.

Once the phone application was downloaded onto the driver's phone, a GPS (global positioning system) location was recorded for the duration the driver ran the app. The app also identified when the driver had traveled less than 500 meters in 15 minutes and would then alert the driver that a "stop" had been made. The app provided a time for the delay, a location tab labeled "where" to show the driver where they were at the time of the recorded "stop" as well as a "reason" tab so that the driver could choose from one of the nine given reasons for the delay in movement. The nine reasons provided were: in woods loading, in-woods delay, waiting at the mill, maintenance/repair, traffic, DOT stop, fueling, personal/meal time, and other. It should be noted that in the options menu a manual fuel stop option was created after realizing that a fuel stop did not take 15 minutes. Stops would accumulate on the main page throughout the day until the driver was able to provide a delay response in case the driver was occupied. Once a reason was provided the "stop" disappeared. At the end of the day (midnight in Greenwich Mean Time) the unanswered delays would clear from the main page so the driver was no longer able to provide a response. This ensured that the drivers' responses were recorded within a "real time" time frame and would have less of a chance for bias. The data was archived in the phone until the driver decided to send the data to the server/google drive.

Once the data had been collected from the server, they were converted to KML files to be viewed in google earth for verification purposes. The routes the drivers took were compared with their delay responses. Polygons were established around the mill and landing areas and all delays which fell within the polygon zone were recorded as a delay for that location.

Results

Final results have not been analyzed at this time. A thorough analysis of the driver's data is scheduled to commence July 2016. A week's worth of initial data from a driver can be seen in table 1 and figure 1. Average delay time at the mill for the driver was approximately 37 minutes and 47 seconds with a minimum time of 21 minutes and 52 seconds and a maximum time of 1:39:47. Logging deck delay times averaged around 32 minutes and 5 seconds with a minimum of 18:54 and a maximum of 1:21:50. This particular logger also delivered wood to a concentration yard which showed an average delay of 24 minutes 34 seconds, a minimum delay of 22 minutes 18 seconds and a maximum delay of 26 minutes 23 seconds.

Table 1.Initial week of data collected by the driver.

(In Minutes)	Mill Delay	Logging Deck Delay	Concentration Yard Delay
Min	0:21:52	0:18:54	0:22:18
Average	**0:37:47**	**0:32:05**	**0:24:34**
Max	1:39:47	1:21:50	0:26:23

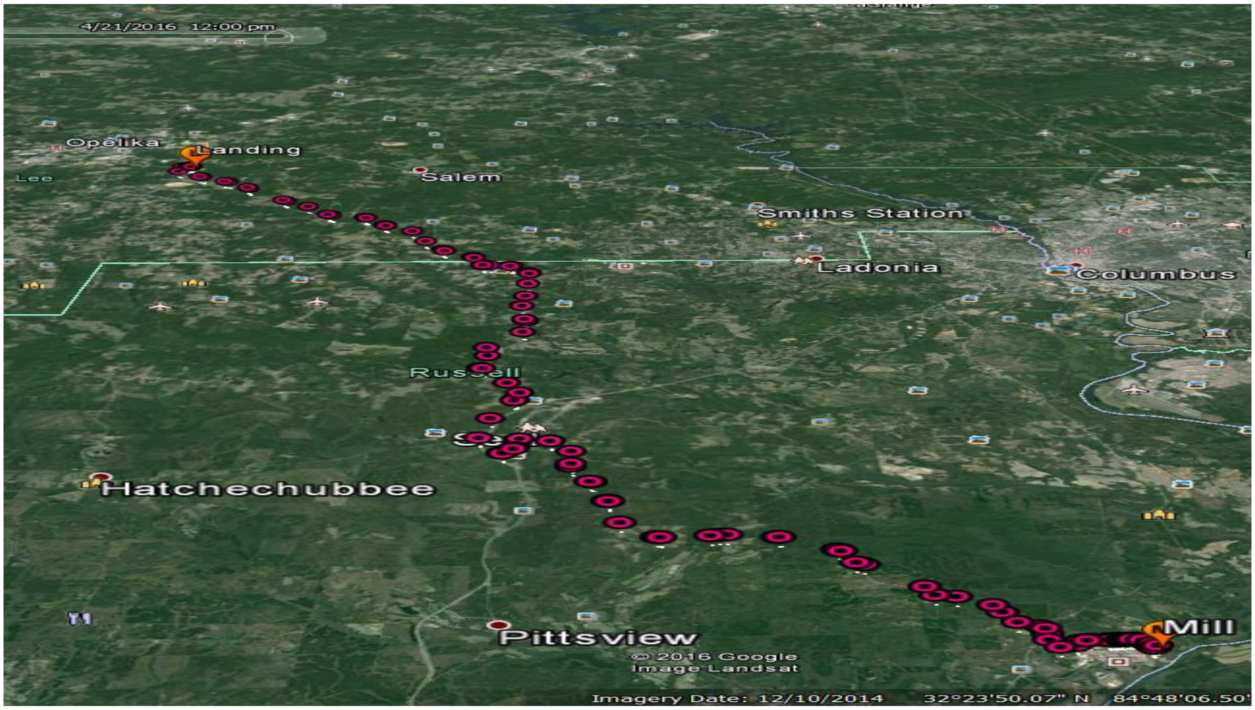

Figure 1. Recorded GPS locations of driver's route between landing and mill. Several trips are depicted on this map.

Discussion

Although no inferences can be made at this time with regards to results, future analysis is expected to determine turnaround times for various mills based on the type of mill and/or region of the mills location. Cycle times for participating loggers will be analyzed and provided to the loggers participating in the study. This information may allow the owner to minimize delays seen by their drivers by choosing alternate routes, repairing any tractors which are causing them significant delays due to breakdowns or DOT (Department of Transportation) stops, providing more accurate haul cost analysis to determine if a tract is economically feasible or even alter their trucking operation more drastically.

Conclusion

Past studies analyzed the delay time at the mill using fleet management systems and GPS's that were installed directly onto the drivers' tractor and provided no means for the driver to identify the cause of their delays. 92% of adults in the United States own a cell phone. 68% of these adults own a smartphone and this number is up 33% from 2011. With over two-thirds of the population possessing a smartphone with GPS, phone app and internet capability an avenue is available to conduct real-time research for the logging industry which may provide explanations to previously unanswered questions. Round trip trucking delays are one of them. This technology allowed drivers to provide an in time reason for a delay they experienced that lasted a minimum of 15 minutes and not moving 500 meters. They were allowed to reply at their convenience for safety and work production reasons as long as the response was before the end of the day. These responses were then archived in a data server to be analyzed at a later time with the end result being an analysis which provided input to minimize haul costs and increase overall economic efficiency.

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Appendixes

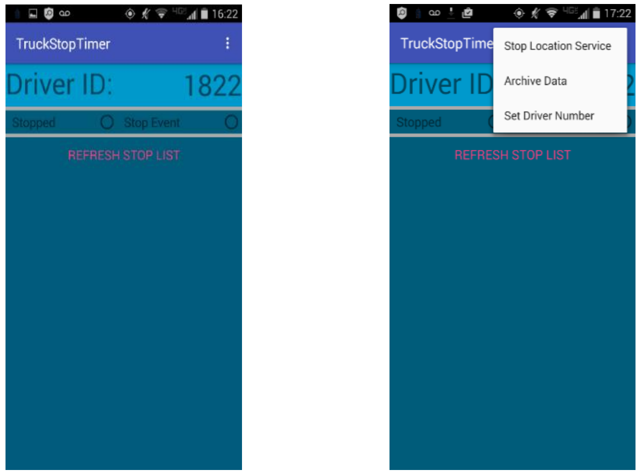

Figure 2. Screenshots of phone application pages used by drivers. The picture on the left is the main page seen, the one on the right shows the options menu which opens after touching the three white dots in the top right-hand corner.

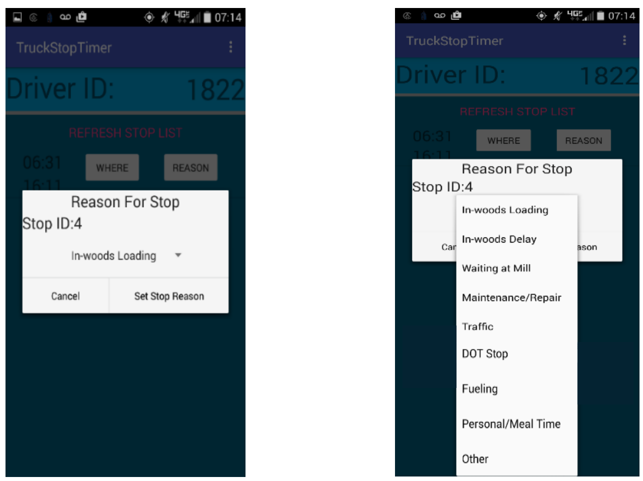

Figure 3. Screenshots of phone application pages used by drivers. The picture on the left depicts a stop which has been recorded while the shot on the right provides the reasons the drivers choose.

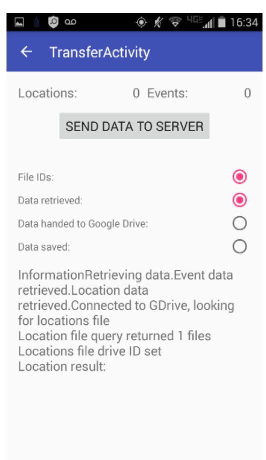

Figure 4. The screenshot above is what drivers see when archiving their data.

Cost, Production, and Effectiveness of Masticated Fireline

Elizabeth Dodson[1]

Abstract

Fire managers are continuously looking for improved methods to construct fireline with minimal resource damage. One option for fireline construction that has so far received limited attention is the use of mastication equipment. This study evaluated a masticating disk mounted on a self-leveling feller- buncher for the cost, speed, and adherence to fireline specifications while constructing approximately 5 miles of fieline across a range of terrain and fuel types. Field trials were conducted during the fall of 2015 on the University of Montana's Bandy Experimental Ranch. Production rates and cost of masticated fireline construction will be compared to traditional handline constructed to the same specifications (30-foot canopy break, 10-foot fuel break, 1- to 3-foot scrape to bare mineral soil). Equipment modifications will be recommended to address lapses in effectiveness as compared to fireline specifications.

Keywords: Wildland fire management; fireline construction

Introduction

Past production rate and cost studies of forest fuel mastication have focused on fuel reduction for wildfire prevention or wildlife habitat enhancement. In certain fuel types and under some burning conditions, mastication equipment may be useful to create fire breaks to assist in the containment of wildland fires. In these situations, mastication would be used to rearrange fuels to slow or stop the spread of fire without the often-excessive soil disturbance created by conventional fireline construction using bulldozers or similar heavy equipment. To date, only one known study has looked at the use of mastication equipment for fireline construction (Clark 2008) and took place during an equipment demonstration project, therefore production and cost results are unreliable. This project estimated production rates and costs associated with using mastication equipment for fireline construction through Northern Rocky Mountain mixed conifer fuel types where mastication is thought to be a realistic method to slow or stop the spread of wildfire.

Suppression of wildland fires accounted for 47% of the total US Forest Service budget in FY 2013 (http://www.fs.fed.us/aboutus/budget/2015/FY15-FS-Budget-Overview.pdf). If masticated fireline is shown to be effective under certain conditions in creating a barrier to fire progress and is similar in total construction cost to dozer- or excavator-built line, masticated fire line may then be more cost effective overall if post-fire rehabilitation work is not needed. A better understanding of masticated fireline production rates, costs, and level of effectiveness under a range of conditions will allow fire suppression managers a wider array of tools to manage a wildfire situation, potentially resulting in more cost-efficient, lower environmental impact fire suppression activities.

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Methods

Study sites were selected at the University of Montana's Bandy Experimental Ranch to represent a variety of slopes and vegetative cover types. The Bandy Experimental Ranch is a 3500-acre working ranch with approximately 2000 acres of forested land typical of many of the forest and shrubland types found across the northern Rocky Mountains. In addition to selecting a range of slopes and cover types, firelines were placed on the ground so as to create logical burning units approximately 10 acres in size that would be appropriate for students to burn at a later date.

Firelines were laid out in 100-foot (30.5 m) segments, GPS location was recorded and temporarily monumented in the field for all segment starting points, general slope information was collected for all segments, and additional site and vegetative cover information was collected for a subset (every-other or every third) of segments. In order to compare masticated fireline construction to standard handline construction, site and vegetation conditions were collected for three zones based on the prescribed treatment: 1-2 foot (0.3-0.6 m) scrape to bare mineral soil at the centerline of the segment; 10-foot (3 m) fuel break (5 feet (1.5 m) either side of the center line) where all vegetation is reduced to ground-level; and 30-foot (9.1 m) canopy break where overstory trees are spaced to at least 10 feet (3 m) between live crowns (Figure 1). All overstory trees greater than 3 inches (12.7 cm) within 15 feet (4.6 m) either side of the centerline were tallied by species and ocular estimate of 2-inch (5.1 cm) diameter class while all woody vegetation (shrubs and trees) greater than 0.5 feet (0.2 m) tall was tallied by species, growth form (shrub or tree), diameter at breast height to the nearest 1-inch (2.5 cm) if applicable, and estimated height to the nearest foot (0.3 m).

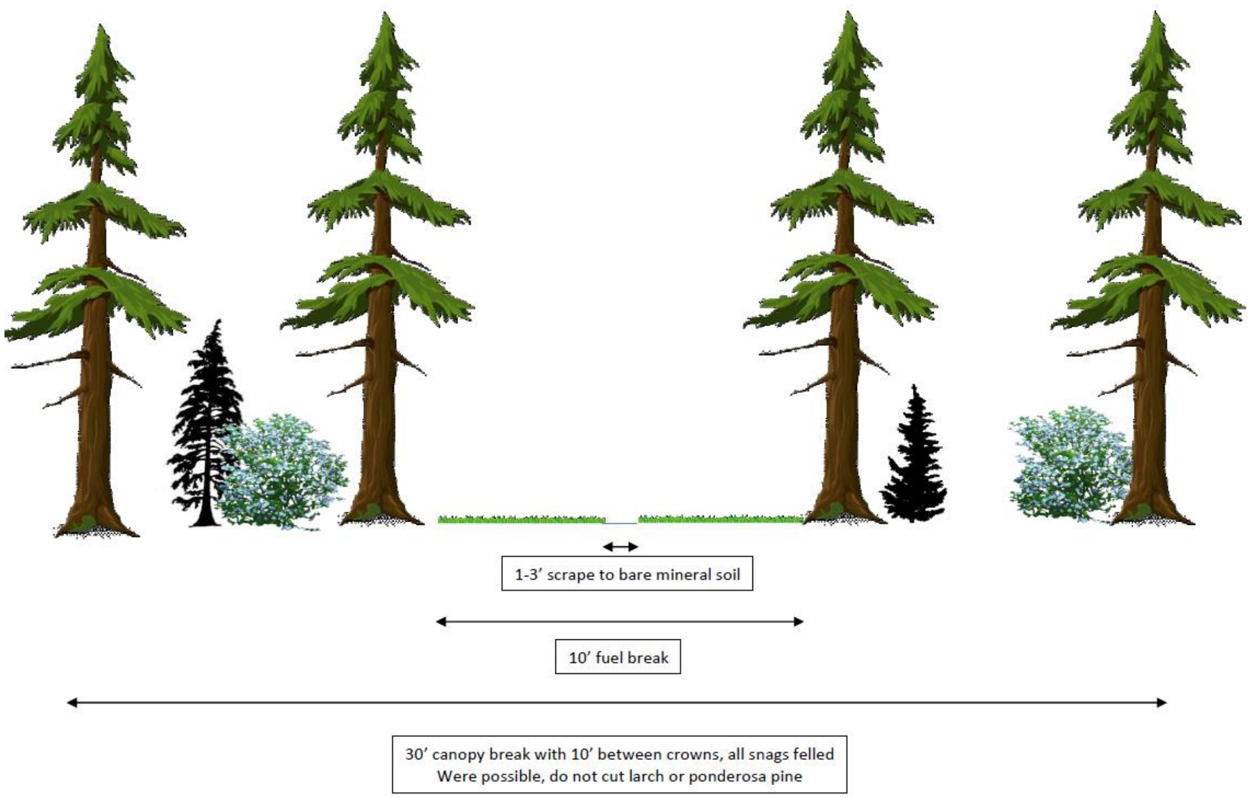

Figure 1: Fireline specifications

A self-leveling tracked Timberjack 608L with a Koehring Waterous disk felling head equipped with a disk containing cutting teeth both around the edge and on the bottom was used for fireline construction. During fireline construction trials, time to the nearest one-hundredth of a minute was recorded for each 100-foot segment and broken into mastication, scrape, travel, and delay time categories.

Effectiveness of fireline construction was evaluated after time trials were completed. Ideally, this evaluation would have been based on performance of fireline under actual burning conditions. As this was not logistically possible, the percent of each fireline segment that was constructed to specification as well as the reason(s) for noncompliance was assessed. A single evaluator paced each fireline segment and recorded the number of paces within each of the following categories: fireline constructed to specification; inadequate scrape to bare mineral soil; inadequate fuel break; or inadequate canopy break.

Results

Three hundred twenty three (323) segments covering 6.1 miles (9.8 km) were located in the field. Of these, complete vegetation data was collected for 125 segments. Slopes ranged from 0 to 54% with an average of 8%. Maximum side slopes were similar with a range of 0 to 56% and average of 10%. Basal area of overstory trees averaged 68.4 ft^2/ac (15.7 m^2/ha) and ranged from 0 to 240 ft^2/acre (55 m^2/ha).

Time and motion data was collected for 263 segments covering 5 miles (8 km) and 36.3 hours. Of this time, 25.5 hours were productive while 10.8 hours were consumed by delays. This results in a utilization rate of 70% and an average delay-free time of 5.8 minutes per 100-foot station or 10.3 stations/hour (313 m/hour). This production rate varied considerably, however, ranging from 1.9 to 93.8 stations/hour ((58 to 2858 m/hour). Considering delays, the average production rate across the range of conditions evaluated was 8.3 minutes per station or 7.2 stations/hour (220 m/hr). At a machine rate of $300/hour (USD), this average production (including delays) equates to $41.56/station, $0.42/foot ($1.36/m), or $2,194/mile ($1,363/km).

Using backwards stepwise regression, productive time per station was found to be dependent on the basal area per acre of trees larger than 3 inches (12.7 cm) within the canopy break, the number of down woody pieces within the fuel break, and the number of rocks greater than 6 inches (15.2 cm) within the fuel break:

$$\textit{Productive time} = 1.970 + 0.036BA + 0.214DWD + 0.038ROCK$$
$$R^2\ 0.6189$$
$$\textit{Adjusted } R^2\ 0.6067$$

Where:

Productive time = delay free time in minutes to construct one station (100 feet) of fireline

BA = basal area of stems greater than 3 inches within 15 feet either side of the centerline, expressed in ft^2/acre

DWD = number of pieces of down woody debris at least 6 inches in diameter within 5 feet either side of the centerline

ROCK = number of rocks at least 6 inches in size within 5 feet either side of the centerline

Comparing constructed fireline to the specifications given in Figure 1 found that only 5% of all firelines met all requirements for the full length of the segment. Less than half of all line constructed (46%) met specifications. The most common failing was an incomplete scrape to bare mineral soil, with 37% of all line constructed in this category. Sixteen percent (16%) of constructed line had an inadequate fuel break, primarily in the form of incomplete mastication of shrubs. Only one portion of one segment of line had an inadequate canopy break.

Discussion

The cost of a Type I IHC (Interagency Hotshot Crew – elite 20-person hand crew) is approximately $7845 per 14-hour day in 2015 USD. Published production rates of Type I IHC crews working in timbered areas (fuel models 8-10) are 10.5 chains/hour (211 m/hr), ranging from 9 to 12 chains/hour (181-241 m/hr), for direct line construction (Broyles 2011). Indirect line construction drops to 6.9 chains/hour (139 m/hr) with a range of 6.0-7.8 chains/hr (121-157 m/hr). This gives an average cost of direct fireline construction of $53.33/chain for direct line and $81.16/chain for indirect line. Comparatively, fireline constructed within this study using mastication equipment cost, on average, $27.43/chain and is likely most comparable to the indirect line construction scenario. It must be noted, however, that the line constructed within this study would require follow-up work, most likely by a hand crew, to complete line to specification. Most of this work would involve completing a scrape to bare mineral soil.

The most common failing in the constructed line within this study was an incomplete scrape. The operator drug the head with the disk stopped to create the scrape, often producing “skips” where the head floated over the ground surface, leaving grasses and forbs intact. One potential solution to this would be to attach a scraper bar on the back of the head such that it is parallel with the ground when grinding. This bar would be easier for the operator to see, would be flat against the ground as opposed to the round hotsaw head, and would be of the desired width for a scrape.

The cost of the mastication equipment used here ($300/hour) is significantly higher than the cost of the same machine used as a felling machine with a standard hot saw disk. There are several anecdotal reasons for this increase in cost. According to the operator who has used the same machine both for felling operations and for mastication, there are several differences in machine performance that impact cost:

- Fuel consumption is approximately 33% higher with mastication as compared with felling. For example, during this study the machine consumed approximately 100 gallons of fuel during a standard 10-hour day. The operator estimated the same machine would consume 70-75 gallons if felling under the same stand and site conditions for a similar amount of time.
- Repair and maintenance time is estimated by the operator to be “at least half again as much” masticating as compared to felling under the same conditions. This is due to the increased stress and strain on the head, boom, and swing functions during mastication. Additionally, the range of motion of the head is much greater masticating as compared to felling. During felling operations, the head generally operates within a few feet of the

ground. With mastication, the head is frequently lifted to at or near full height in order to reach tall shrubs and trees.

- During full-time mastication work, this machine will generally go through a full set of grinding teeth (the teeth on the bottom of the disk) in a standard work day. The 2015 cost of a set of grinding teeth was approximately $400. Wear of cutting teeth (those teeth around the edge of the disk as on a standard hot saw disk) would be higher, but more similar, to standard felling operations due to the increased likelihood of hitting a rock while masticating.

This particular machine was chosen for this study based on its ability to fall and bunch merchantable stems similar to a feller-buncher. This was viewed as important when constructing line through forested areas. Based on experience during this trial, it is not recommended to use mastication equipment not capable of felling large stems in forested areas unless some other means of felling and bunching are utilized, which then removes the advantages of a single machine. Therefore, production rates and other results of this study should not be extrapolated to other mastication equipment that does not have this felling capability.

From this study, it is unclear if line constructed using mastication equipment would need less rehabilitation work after a fire than standard line constructed using "traditional" methods of hand crews, crawler tractors, or excavators. This may be the case if no scrape is constructed; however fire managers did not view such a line (one that only contains a fuel and canopy break) as an effective control line.

Conclusion
Mastication equipment was used to construct fireline at a cost of approximately one-third that of a Type I hand crew. The equipment used in this study had difficulty maintaining a consistent scrape to bare mineral soil; however it is felt an inexpensive machine modification could greatly improve the performance of the equipment in this aspect of fireline construction.

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Citations
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Assessing the Emissions and Costs of Disposing Forest Residues using Air Curtain Burners

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Abstract

Forest residues generated from timber harvests, fuel reduction thinnings, and drought/insect/disease damage need to be managed. Limitations on open pile burning and woody biomass utilization for energy have lead land managers to look for safe and economical disposal methods. Recently, a new biomass incineration box produced by Air Curtain Burner (ACB) has gained considerable attention as an alternative method of disposing forest residues. The objective of this study was to describe the emissions and costs associated with disposing forest residues using ACB and evaluate its performance. We conducted a literature review to better understand the emissions generated from systems typically used to comminute and transport material out of the forest. These emissions were then compared with those generated by the ACB. We also performed three field-based controlled experiments to evaluate biomass consumption rates and costs of disposing forest residues in Jacksonville Florida, Groveland and Volcano California. The literature revealed a 75 and 95% reduction of Carbon monoxide and particulate matter ($PM_{2.5}$), respectively, when using ACB. The overall cost to operate the S-220 ACB ranged from $ 17.22/green ton (GT) to $ 20.07/GT. Costs were more ($ 38.93/GT to $ 136.63/GT) when using the BurnBoss ACB unit. Our results show that burning forest residues with an ACB can be an environmentally conscious method of disposing forest residues.

Keywords: open pile burning, a new biomass incineration box, S-220, BurnBoss

1. Management of forest residues

Forest residues comprised of non-merchantable wood such as branches, tops, and chunks are generated during timber harvests, fuel reduction thinnings, and the removal of drought/insect damaged trees (Smith et al. 2009; Sprinsteen et al. 2011). Open pile burning is the most prevalent method of disposing forest residues in western U.S. (Springsteen et al. 2011). However, this method has many concerned as it produces smoke impacting human health and runs the risk of embers escape, even though burning is only allowed in very narrow conditions (Lemeux et al. 2004; Jones et al. 2010). Additionally, burning slash piles has undesirable effects on soil properties which are commonly more severe than wildfire or broadcast burning (Certini, 2005; Hubbert et al. 2013). This is due to the fact that compared to other burning, open pile burning can be heated much longer and are more intensive leading to greater fire intensity at deeper depths (USDA. 2015).

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The extraction of forest residues for utilization as an alternative to open pile burning, can be technically feasible, however, there are many challenges including high costs associated with the collection and transportation (Grado and Chandra, 1998; Sun and Zhang, 2006; Han et al. 2010). Since the latter half of the 1990s, biomass utilization has decreased significantly due to a drop in natural gas prices (Morris, 2003). At the same time, more than 55% of California's wood-based power plants have shut down (Morris, 2003). For this reason, forest residues and mill waste have been piling up in forests and saw-mills. The markets for forest residues-based bio-power (e.g., heat and electricity) are primarily limited to power plant in northwestern U.S. (Kizha and Han, 2015).

In this study we described an alternative technology to dispose forest residues using an Air Curtain Burner (ACB; Air Burners, 2015). This method's approach effectively allows for removal of hand-piled slash in forest, paper trays next to forest road, and piled high at the landing from accessible area without open pile burning. This helps avoid the negative effects of air quality and spread fire, restriction on burning season, and market forces of biomass fuel value. ACBs use a moving curtain of air to circulate greenhouse gases and particulate matter emitted from combustion. The curtain oxygenates the fire within in the box which improves its consumption rate (Figure 1). Past studies have focused primarily on the emissions generated from ACBs, however these studies haven't included the greenhouse gases and particulate matter, making the data less useful. In addition, none of these studies assessed the costs of disposing forest residues.

Our objectives in this study were to: 1) to conduct a literature review to summarize the amount of emissions data including carbon monoxide (CO) and particulate matter (PM) (Fountainhead Engineering and Deruiter Environmental, Inc. 2000; Zahn, 2005; Air Burners, Inc. 2015) and 2) to calculate the cost of disposing forest residues for S-220 with a fire box size of 19'8" (L) × 6.2' (W) × 7'1" (H) and two types of BurnBoss that with a fire box size of 12' (L) × 4' (W) × 4' (H) through field-based experiments.

2. Study Methods

Emissions of CO and PM from burning and extraction of forest residues

A detailed literature investigation was performed to collect available data describing emissions of ACB burning of the forest residues for disposal. We focused our review on the emissions of CO and PM, as they are considered two of the top six air quality pollutant that can aggravate and or lead to a number of serious health problems (EPA, 2016).

Costs of disposing forest residues using ACBs

The study sites for the field-based experiments were located in Jacksonville, Florida, and Groveland and Jackson, California. The S-220 was tested in Jacksonville, Florida. The main species burned at this site were Lolly pine and less than 20% of local hardwoods. S-220 operation required a rubber-tire front-end loader and water truck during the burning process. For the study we tested also two different BurnBoss units; one in Groveland, CA and another equipped with a screen to catch embers in Volcano, CA. At the Groveland study site we burned 80% Ponderosa pine and 20% manzanita shrubs. Only Ponderosa pine was burned at the Volcano study site during the test. Both BurnBoss units were loaded by hand, and included a pickup truck and water truck during the burning process.

A time and motion study using a stopwatch was performed to calculate the burning costs. In order to evaluate the biomass consumption rates, material was loaded onto a truck and weighed using a wheel load scale (PT300^{TM} RFX. Rice Lake Weighing Systems. Rice Lake, WI). The moisture content of the materials greater than 4" was determined by sampling cookies and for materials less than 4" by sampling branches and needles. Samples were oven dried (105 °C for 62 hours) to constant weight loss. The following describes the cycle for the burning activity phase:

- The process of ACBs from set-up to finish begins by starting from the setup on level ground, first loading smaller materials (less than 4") for kindling, igniting with torch, turning on the air blow, second with loading with slash or waste wood and waiting for the materials to burn down to ash. In particular, the second loading pile is not dumped higher than air curtain in the box.

- S-220 test: Burning time recording was started when the air blow turned on and ended when the last materials were loaded.

- BurnBoss test: Burning time measurement was started when the air blow turned on. This obsevation was based the time it took to completely burn the materials down to ash.

A "cold start" method was used for every test. A "cold start" means that each burn started on bare ground (i.e., no ash from a previous fire) and required the inginition of kindling, followed by the addition of larger fuels until the fire burned on its own. Hourly machine costs measured in $/Scheduled Machine Hour (SMH) were calculated using cost analysis method by Brinker et al. (2002. Table 3). Overhead or indirect, profit allowance costs and permit fee were not included.

3. Results and Discussion

Emissions released from ACBs burn

One of the greatest advantages of using an ACB is that there is hardly any smoke or ember when burning material (Figures 1 and 2). A detailed study on burning waste wood materials in a S-127 model ACB was performed by Fountainhead Engineering and Deruiter Environmental, Inc. (2000). They recording CO emissions at 0.11 lb/ton with a total PM emissions of 0.01 lb/ton. Jeffery pine and Douglas-fir slash was combusted in a different study by Zahn (2005). They used the same Air Curtain machine and observed CO emissions of 28.15 lb/ton and $PM_{2.5}$ (particles less than 2.5 micrometers in diameter) emissions of 1.25 lb/ton. Air Burners (2015) reported that CO emissions of 1.11 lb/ton and $PM_{2.5}$ emissions of 1.10 lb/ton were generated in 5 different regions when wood waste was burned using S-220 and S-327 model ACBs. Differences in CO emissions can be explained by the velocity of air blown over and into the fire during operation.

This velocity is controlled by engine speed. When the engine exceeds 2,500 RPM, the result is that greenhouses gases and smoke increase and embers are typically ejected (Air Burners, 2016).

The emissions of open pile burning had CO levels ranging from 120.67 to 228.80 lb/ton and $PM_{2.5}$ levels 9 to 26 lb/ton (Andreae and Merlet, 2001; Jones et al. 2013; Baker et al. 2014; Springsteen et al. 2011 and 2015; Air Burners, 2015). The ACBs reduced CO and $PM_{2.5}$ emissions by 92-95% compared to open pile burning. $PM_{2.5}$ were more (4.39 lb/to) when using the biomass recovery operation (Air Burners, 2015). In particular, the top part curtain of the air is designed to keep a large proportion of CO and PM during the burning (Miller and Lemieux, 2007).

Costs of burning forest residues using ACBs

Forest residue consumption rates and cost of disposal calculated from each test varied considerably and were dependent on machine capacity, material size, and species (Table 4).In the experimental result of the S-220, the major factors that affected the burning consumption rate was the species. In particular, this rate was related to moisture content, wood density and chemical composition (White, 2000). For example, softwood is known to easily ignite while burning up quickly. Furthermore, when using the BurnBoss unit the burning consumption rate was affected by material size. The greater than 4" materials took longer to burn to completion and similar pattern have been shown in previous studies (Hubbert et al. 2013; Wright et al. 2015). Because this, materials are slower to lose moisture, there is less reduction of pile volume.

The disposal of forest residues using ACBs would be an economically viable alternative to open pile burning method, which costs ranged from $180 to $1,540/acre (FAC Network Participant, 2015). Furthermore, biomass recovery operations are sensitive to market prices. Recently low natural gas prices have made biomass recovery operations economically impractical, therefore more forest residues are being left piled up in the forest (Jones et al. 2013). Overall, ACBs are possibly useful to disposal of forest residues regardless of the market.

4. Conclusion

The ACB was developed to reduce the emission of CO and PM. An emissions database of three different forest treatment residues was developed from previous studies and the costs were calculated through field-based experiments. The ACBs reduced CO and $PM_{2.5}$ emissions by more than 75-95% compared to open pile burning and biomass recovery operations. ACBs would be an environmentally viable alternative to these methods. The S-220's cost of disposal ranged from $ 17.22/GT to $ 20.07/GT. On average the BurnBoss cost was calculated to be $ 63.46/GT and $ 121.33/GT for material under and over 4" diameter, respectively. Factors such as machine capacity, material size, and species all affected operation costs of ACBs. This study shows that ACBs could be useful to dispose forest residues when open pile burn or biomass utilization is not a feasible option.

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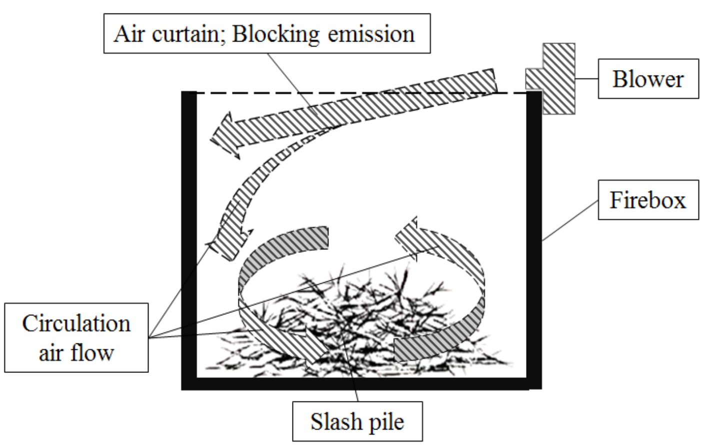

Figure 1. Principle of Air Curtain Burner while this machine is turned on.

Groveland, California

Volcano, California

Figure 2. Comparison of the smoke between ACBs and open pile burn. The picture of the same time period, (a) BurnBoss and (b) open pile burn.

Table 1. Summary of weather condition during the burn tested.

	Air temp (°F)	Humidity (%)	Wind speed (miles/hour)
Jacksonville, Florida[a]			
Softwood	85.5	95.4	
Hardwood	87.6	87.0	N/A[b]
Mix[c]	86.0	81.2	
Groveland, California[d]			
Softwood < 4"	74.8	38.1	1.8
Softwood ≥ 4″	68.1	59.2	1.5
Volcano, California			
Softwood[e] < 4"	67.0	37.8	0.5
Softwood[f] ≥ 4″	76.0	28.7	0.8
Softwood[g] ≥ 4″	86.3	35.8	0.3

[a] Materials from timber harvesting.
[b] Not avaliable data.
[c] Mixed with species.
[d] Fuel reduction thinning residues.
[e] Drought/insect damaged trees' top and branch.
[f] Drought/insect damaged trees' stem wood.
[g] Fuel reduction thinning residues.

Table 2. Summary of material size, moisture content, and crew needed for the three different burning experiments.

Locations	Material size (diameter in inches)	Moisture contents (%)	Crew (
Jacksonville, Florida			
Softwood	6.0 - 8.0	36.7	
Hardwood	8.0 - 15.0	35.5	2
Mix	6.0 - 14.0	33.4	
Groveland, California			
Softwood < 4”	2.0±0.1	26.0	1
Softwood ≥ 4”	7.4±0.4	27.4	
Volcano, California			
Softwood < 4”	2.4±0.1	19.0	
Softwood[a] ≥ 4”	6.2±0.5	31.5	1
Softwood[b] ≥ 4”	6.2±0.5	17.1	

[a] Drought/insect damaged trees’ stem wood.
[b] Fuel reduction thinning residues.

Table 3. Summary of cost factors and assumption used to calculate hourly costs.

Machine	Initial price (US $)	Utilization rate (%)	Actual machine rate[a] (%/day)	Hourly cost[b] (US $/SMH)
S-220	106,000		100	87.18[c]
Loader	135,000		30	9.22[d]
BurnBoss	48,900	75	100	28.48[e]
BurnBoss[f]	49,900		100	28.62[e]
Pickup truck	40,000		10	0.73[d]
Water truck	40,000		10	0.74[d]

[a] Based on field experiments.
[b] Including actual machine rate.
[c] Involving wage of two crews.
[d] Excepted a wage.
[e] Including wage of one crew.
[f] BurnBoss with ember screen.

Table 4. Cost of disposing forest residues using ACBs method.

Locations	Burning consumption rate (GT[a]/SMH)	Operating cost[b] (US $/SMH)	Cost of disposal (US $/GT)
Jacksonville, Florida			
Softwood	4.84	97.12	20.07[c]
Hardwood	5.42		17.93[c]
Mix	5.64		17.22[c]
Groveland, California			
Softwood < 4”	0.77	29.94	38.93[d]
Softwood ≥ 4”	0.30		100.28[d]
Volcano, California			
Softwood < 4”	0.34	30.08	88.00[d]
Softwood[e] ≥ 4”	0.24		127.07[d]
Softwood[f] ≥ 4”	0.22		136.63[d]

[a] Green ton at the moisture content levels shown in Table 2.
[b] Including hourly cost of air curtain burner loader (Jacksonville), wages, and a water truck.
[c] Burning time recording was ended when the last material was loaded: there was still a full load of wood residues, in firebox. Then, it was allowed for the operator to leave from the site while burning was in progress.
[d] For the experiment, completed in Groveland and Volcano, the burning time measurements were based the time took to completely burn the materials down to ash.
[e] Stem wood from drought/insect damaged trees.
[f] Fuel reduction thinning residues.

Forest trucking industry in Maine: A review on challenges and resolutions

Anil Koirala[1] Anil Raj Kizha[2] and Brian Roth[3]

ABSTRACT

Hauling timber material from in-wood to the final point of utilization has always been a major component influencing cost of the entire forest operations. Although past researchers have focused on various aspects of transportation, challenges to the forest trucking are by far unnoticed. This study mainly focused on synthesizing information from published literature on various features related to trucking in general and with special emphasis on the state of Maine, USA, eventually, leading to identify specific problems related to the wood trucking industry and their probable resolutions. Forty literature including peer-reviewed articles, technical reports, trade magazines, and government documents were reviewed to comprehend the fundamental aspects of trucking for sawlogs, pulpwood, and comminuted biomass. This study has made an attempt to identify a different range of options for trucking under various conditions, such as road types, terrain, climate and economical features. Altogether eight major challenges with potential resolutions adopted in different regions were discussed and compared to the working conditions in Maine. This paper is expected to support the understanding of problems in general and fill the gap of knowledge regarding trucking for the state. Land owning, & managing, trucking, and logging companies would be able to use the results from this study to prepare trucking plans to support logistics based on given circumstances. These findings can also be used as a baseline figure for further studies involving logistics and supply chain analysis for the logging industry.

Keywords: *Hauling timber, secondary wood transportations, logistics, supply chain analysis*

1. INTRODUCTION

There is no doubt that transportation is one of the major components of forest operations and, from citizen's perspective, the most visible and appealing section of the entire forest management scheme from plantation to the utilization of the trees (Murphy 2003; Greene et al. 2007). A significant portion of timber harvesting has to do with transportation of wood products. In the forest products supply chain, transportation cost constitutes a major portion of the total production costs, from planting to the mill. Different researchers (Pan et al. 2008; Kizha. et al. 2015) had reported that transportation accounted for about half of total production cost in the forest products supply chain. Even a small increase in the efficiency in transportation could help in minimizing the overall "stump to gate" production costs. As forestry and natural resource sector are major contributors to the state of Maine's GDP, the importance of forest products transportation cannot be undermined.

After the last log drive on the Kennebec River in 1976, transportation of woody commodities from northern forests has predominantly been performed by road (MFPC 2013).

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Different types and configurations of trucks and trailers are used depending on the types of raw materials to be hauled. There are mainly three categories of forest raw materials: pulp logs for pulp and paper mills, saw logs for sawmills; and energy woods and wood chips for energy plants as well as paper mills (Epstein et al. 2007). All of which have separate trucking fleets specifically designed for each. Tractor trailers and fixed truck types are generally used to transport forest products. The road tractors are used to pull the trailers that can be open log trailer or closed cargo trailer. These trucks are versatile in terms of changing type, size and configuration of cargo or trailers to be hauled (Schroeder et al. 2007). The chip vans are another type of trucking system specially designed for transporting wood chips and hogfuels. They are closed box trailer; with an open end or top; commonly pulled by road tractor.

Transportation of forest products is influenced by many travel circumstances. Among which, travel distance, truck configurations, road conditions, geographic condition, climate, and markets are important. Road factors such as alignments, width, gradient, elevation along with truck characteristics and load size are also influential. The types of woody materials transported can also affect travel speed and transportation cost (Han and Murphy 2012). Woody materials can differ in bulk densities and moisture contents, which can affect legal maximum payload carried (Fig.1). Low bulk densities and high moisture content in materials can inversely affect the transportation cost while the use of denser loads with lower moisture content will help in getting maximum payloads, thereby, decreasing transportation costs (Talbot and Suadicani 2006).

Figure 1. Grinder feeding a highway tractor with hog fuels. These trucks are often restricted by volume and not weight depending on the states they operate.

Forest products industries; being the major job providers in the state: has employed over 2,700 truck drivers (excluding self-employed operating as sole proprietors) in 2011 (MFPC 2013). The problems faced by forest trucking industry have been noticed for many years but effective research identifying the problems, seeking out the solutions, and integrating has only been done on a limited basis in Maine.

The purpose of this study was to determine problems and challenges faced by forest trucking industry in the state of Maine. The truck-turn times at harvesting and processing facilities along with the possibilities of utilization of empty trucks in the period of back-haul without excessively slowing down sawlog hauling were also focused. This study has also listed potential resolutions to problems in forest trucking that were adopted in other parts of the country and globally. Forest-based industries may use the results of this study to increase the efficiency of their secondary transportation procedures for making sound harvest and transportation plans.

2. METHODOLOGY

Literature concerning wood transportations, including scientific articles, technical reports, professional society's publications, government records, trade magazines, newspaper reports and graduate theses were studied to identify challenges faced by the forest trucking industry and deduce potential resolutions. Altogether, 65 literature related to different aspects of trucking were selected, out of which 40 literature were used for this study. More specifically 27 peer-reviewed journal articles, 6 technical reports, handbooks, trade magazines, 1 conference proceedings, 3 graduate theses and 3 miscellaneous documents: - a directory, a training curriculum, and a state regulation; were used for this study. All recent publications were used Publication date of the literature ranged from years 2000 to 2016. Conclusions were made according to authors' point of views summarizing different informal information.

3. CHALLENGES FACED BY FOREST TRUCKING INDUSTRY AND RESOLUTIONS

3.1 Design and fuel efficiency of trucks

Trucking, in general, is facing a new perspective of environmental concerns as 22% of global CO_2 emission is caused by road freight (McKinnon and Piecyk 2009). This is of special concern to the forest products trucking as most log trucks are older than common long haulage trucks. Conventionally, most of the log trucks initially operated in non-forestry purpose and were later modified into log trucks after certain years of operations (Gallagher et al. 2005; Tufts et al. 2005b; Dowling 2010). However, new trucks are also operating in substantial quantities.

There are various specifications that affect overall performance and fuel efficiency of trucks, including engine, design, speed, number of axles, trailer types and length (Tufts et al. 2005a; Geisler et al. 2016). Fuel consumption is positively related to the overall transportation costs, which further depends on travel time. Selection of proper trucks with suitable specifications for different road types ranging from interstate and state highways to rough and muddy forest roads is very crucial in forest transportation.

Design of trucks is primarily based on necessities and vary by regions. For example, North eastern states tend to use more self-loading log trucks compared to the Pacific northern states of US. This practice eliminates the need for a loader in woods, however, could negatively affect the loading productivity and hauling capacity. Proper selection of trucks and trailers designs can often be logistically challenging due to situations faced by trucks from off-road mountain path to slippery snowy path (Zhang and Tabarrok 2000; Zamora-Cristales and Sessions 2015). Trucking productivity is highly influenced by road conditions and speed of the truck itself.

Design, size, weight and technologies along with environmental restrictions to operate are regulated by federal and state laws. Appropriate choice of engine size, correct axle ratio and desirable maximum speed of the vehicle are required for enhancing fuel efficiency (Lautala et al. 2015). On road techniques such operating in lower level of *rpm* (revolution per minute) also improves fuel efficiency (Tufts et al. 2005b). Fuel consumption is maximum during acceleration, therefore, it is recommended to avoid transportation routes with frequent stops, traffic lights, multiple turnings and fluctuating gradients. Utilizing trucking simulator (attached to later models) can help to determine the best combination of these components (Barrett 2001). Regarding the design of trucks and trailers different axle combinations can be used for specific situations such as- large single trailer combination for flat terrains whereas double small trailers for steep terrain with sharp bends and curves (Han et al. 2010; Zamora-Cristales and Sessions 2015).

3.2 Modelling supply chain for efficient logistics

Log trucks and chip vans have to operate in different types and standards of road networks, which makes trucking a challenging job to perform. Trucks should be adaptable to low-quality forest roads as well as high standard public highways. Cost of road construction is another significant factor that can affect overall cost of forest operations. Forest transportation is different than other transportation sectors as it requires construction and maintenance of vast amount of private road networks inside and outside the woods; and designation of loading and landing sites within the harvest unit and occasionally on secondary loading sites (Bont et al. 2012). Planning of convenient and cost-effective route and locating the easiest path that would connect every station within one harvest operations are often desirable in forest road design.

Various modelling approaches have been adopted to design and layout the forest roads in minimum possible costs in Europe, Asia, South and North America such as- mixed integer linear programming to layout truck routes (Bont et al. 2012); combinatorial heuristic approach for solving road design problem (Epstein et al. 2006) ; vector based road network projection (Kizha et al 2015), automatic road network planning using spatial modelling (Stückelberger et al. 2007); and forest road network design using trade-off analysis (Chung et al. 2008). Apart from this, improvements of main forest tractor roads to the truck roads and enhancement in landing space can also be helpful in improving the trucks performances. Similar practices were carried out in Italy and suggestions were made to improve and enlarge forest road networks to lower woodchips supply costs (Cavalli and Grigolato 2010).

3.3 Geography and climate

Geographical condition of the harvesting and loading sites directly effects the cost of road construction and selection of appropriate truck and trailer types. The productivity and cost of transportation are also highly influenced by the type of terrain. Rough terrain and narrow road conditions lead to increased time for maneuvering and high waiting times for passing trucks. In addition to the costs, steep terrain can pose a serious safety risk; therefore, are not highly preferable for transportation.

Climate is another important factor to consider. Harvesting and transportation of forest products are conducted in certain permissible windows of a year and vary regionally (Kizha. et al. 2015). Generally, harvesting operations are preferred in winters in temperate regions having high snowfall like Maine, New York, Vermont, Minnesota, etc. (Fig. 2) in order to avoid soil displacement from lowlands and wet areas due to the hard and frozen conditions (Abbas et al. 2011). However, winter operations also pose other challenges such as the winter road maintenance including snow removal and use of anti-slip measures (Malinen et al. 2014). Severe weather conditions including poor visibility, big snowstorm, and heavy rainfall can easily disrupt the on-going operations any time. In regions receiving relatively high rainfall, such as Northern Pacific Coast, harvesting operations are carried during summer. Forest roads are also closed during rainy season.

Figure 2. Winter roads constructed by a loader for transporting forest products in Maine. Winter roads are comparatively cost efficient in construction and maintenance compared to paved forest roads.

3.4 Back-hauling of the empty trucks

Transportation efficiency decreases almost by half when trucks travel empty from mill to harvesting sites (Amrouss et al. 2016). The best solution for this problem is utilizing empty trucks haul other loads while returning to the harvesting site; also referred to as back-hauling. Proper planning and coordination with other contractors, loggers, mills or even non-forest products business could help in reducing the frequency of empty rides. Opportunities for backhauling mainly depend on the type of transportation as well as the geographical distribution of harvesting sites and receiving facilities. Identification of appropriate and convenient routes are also significant factors to be considered during back-hauling. These efficient routes should involve direct transportation between supply and demand points so that the empty phase of the trucks can be minimized (Carlsson and Rönnqvist 2007). But back-hauling of empty trucks is a challenging job, as trucks used in forest products transportation have their own characteristics; some are specialized for round log transportation whereas some are specialized to carry processed products as chips and pellets. Additionally, backhauling can lead to operational delays in transporting phase, therefore, might not be suitable for operations constrained by landing space and harvesting timeframe. Hence, it is often difficult to utilize the trucks for back-hauling if not planned properly (Epstein et al. 2007).

3.5 Increased truck turnaround times

Turnaround times of the trucks used in forest products transportation is very crucial in forest operation and has major impacts on entire operation efficiency and cost. Even slight increments in truck turnaround time than usual could negatively affect the companies in the long run. The major reason for operational delay at the harvest site is associated with the waiting time for loader to be available, which can delay the operations of the trucks and increase the overall costs. Such situations are common in operations with limited landing space (Kizha. et al. 2016). Therefore, it is imperative to have proper coordination between different machine operators at landing, as well as efficient loading mechanisms to save trucks waiting. Also determining the appropriate number of trucks would be desirable for efficient and continuous transportation without any delays. Dowling (2010) reported a case study where timber trucks spend about 32% of their time in harvesting sites being unproductive. Self-mounted trucks are also another option for reducing waiting time at the harvesting sites. Space of landing can be of significant importance in case of turnaround time. The landing space not only increase the place to pile up harvested as well as unloaded materials, it also provides proper space for turning and waiting for the trucks.

At the receiving facility, use of more unloading equipment during peak business periods as well as enhancing the efficiency of the mechanism can reduce significant waiting time (Fig. 3). Coordination between drivers and the end use facility also plays a major role in minimizing turnaround time. Drivers can even avoid the mill in peak hours and can come back later through proper communication.

Figure 3. Trucks being unloaded at mill yards. Sufficient number of loaders can reduce waiting time on trucks.

3.6 Location and Availability of Market

In Maine, six pulp and paper mills have been closed in past five years. These closures has directly and indirectly affected the forest trucking industries as well. The location of forest products industries and markets is directly related to transportation cost. The forest product industries being highly scattered in Maine and trucks have to travel long distance to deliver materials (Lilieholm et al. 2011; NEFA 2013). A nationwide study reported that the average hauling distance for softwood sawlogs and pulpwood was highest in the Northern states of US, which increased the price of the product substantially compared to other regions (Libbey 2000).

3.7 Different types of loads and weight restriction

There are state and federal regulations for loads and weight specifications of log trucks. The New England Transportation Consortium (NETC) involving Maine, New Hampshire, Massachusetts, Vermont and Rhode Island, developed a common set of standards for the movement of oversize/overweight combination vehicles. The NETC permits 108,000 pounds weight limit for five-axle and 120,000 pounds for six or more axle truck tractor-trailer combination vehicle (BMV Maine 2012). Maintaining the legally allowable payload with tree length required by the mills is a very challenging job. The empty weight of the trucks without any loads is tare weight of the trucks, which is combined with the load to make a total truckload. So, it is desirable to minimize the tare weight of the trucks as low as possible, by removing unnecessary equipment that have been attached to the trucks and trailers (Shaffer and Stuart 2009). Regarding legal allowable payload, it is usually hard to maintain the maximum load with low bulk density forest products such as comminuted wood biomass (Schroeder et al. 2007). The bulk density of these products can be increased by proper compaction of the products while the allowable load can be met by selecting different arrangements of trucks and trailers combination (Shaffer and Stuart

2009). Knowledge on different types of truck loads and weights are also important for assessing the damage caused by the trucks on the roads (Owusu-Ababio and Schmitt 2015).

3.8 Lack of skilled manpower

A recent survey reported the main challenge among trucking companies was to find, retain and develop talents i.e. skilled drivers; and predicted it to be more acute in the coming years (HireRight 2015). The American Trucking Association (ATA) estimated overall current truck driver (including forest transportation) shortage is more than 35,000 individuals and 240,000 additional truck drivers will be needed by 2023 (Costello and Suarez 2015). The trucking industry is heavily dependent on drivers 45 years of age and older, a report published by American Transportation Research Institute (ATRI) in 2014 showed that the median truck driver age was 46.5 versus 42.4 for the overall U.S. workforce in 2013 (Short 2014). These indicate the shrinking size of the core working age population (21 to 50) in forest transportation sector. There are very limited studies that focused on the reasons behind the drivers' shortage and the trucking itself, as trucking is always believed to be a banal thing to study. The respondents from the same survey by HireRight indicated that the main reason behind the drivers leaving the organization was due to low wage offered, followed by extended time away from family and to get lesser benefits for the truck drivers, in general, compared to other jobs. One of the main resolution that can retain and attract skilled drivers in the companies would be the pay increment. Upgrading the equipment, bonus program, and performance based reward program can also be beneficial for the retention. Independent contract schemes along with ownership sharing mechanism are in use in Finnish forest products industry (Palander et al. 2012).

4. CONCLUSIONS

Management of trucking challenges is crucial for efficient forest operations. Several factors can contribute in maximizing trucking productivity. Altogether eight managerial challenges were reviewed in this article. These challenges were selected based on the objective of the study and recommendations from experienced loggers and foresters. The resolutions discussed were from various regions.

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A multi-criteria decision making approach to locate a terminal in bioenergy supply chains

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Abstract

Forest biomass is a promising feedstock for energy production because of its carbon neutrality and its potential for stimulating regional economies. However, it is voluminous with large variability in quality, and its supply is exposed to various uncertainties. Customers require a uniform feedstock with security in supply. A terminal in the supply chain can help overcome these challenges. Biomass can be treated in the terminal to meet customers' quality specifications. Inventory can be stored in the terminal to overcome supply disruptions. Nonetheless, terminal requires a significant capital investment, and once installed, the decision is practically irreversible. Thus, the decision to install a terminal needs to be made judiciously. The decision process must account for diverse factors that influence the terminal's effectiveness. These factors are both quantitative and qualitative. There is not yet a consensus on the set of factors that should be taken into consideration in evaluating the potential location of a terminal. This research aims to (i) identify the most important factors that should be taken into consideration in locating a terminal, (ii) propose a multi-criteria decision-making framework that allows different factors to be considered in choosing a terminal. The framework consists of analytical hierarchy process (AHP) to analyze qualitative information, and a mixed-integer programming model to evaluate quantitative information. The framework was implemented to a case study in Eastern Canada. It proved to be a practical and effective tool for identifying terminals with the greatest probability of maximizing value for the bioenergy supply chain. Further investigation is required to develop environmental and social criteria.

Keywords: MCDM, MIP, AHP, log yard, forest industry.

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Introduction

Increased environmental awareness around the world is giving way to the green economy (Hanna 2010). Similarly, in the energy sector, alternative, carbon neutral feedstocks are being explored. The forest industry is well positioned to support this development (FPAC 2011). Forest residue are readily available to support the energy sector. Forest residue includes tree tops, branches and trees not desired by the conventional forest industry (Gautam 2010). It also includes trees damaged by fire, wind or other types of disturbances (Boukherroub et al. 2015). Utilization of residual biomass also presents the forest industry with an opportunity to diversify its market and improve competitiveness (Alam et al. 2014). However, despite the abundance of logging residue, its financial feasibility for energy production is highly sensitive to a number of factors. Biomass delivery system consists of harvesting, storage, processing and transportation (Gautam et al. 2010). Each subsequent activity adds a significant amount of cost because biomass is a feedstock with low energy density and a high rate of incombustible material (McKendry 2002). Handling and transportation of this voluminous feedstock is inefficient in comparison to fossil fuels. Furthermore, there is a high variability in quality because wood is a biological material (Gautam 2012). As such, feedstock qualities change rapidly and even deteriorate if not handled appropriately. Quality, particularly moisture content, is important from a logistical perspective as well as during combustion. High level of moisture content makes transportation of biomass inefficient to a level that the entire operation becomes infeasible. During combustion, particularly for small and medium scale boilers, moisture and ash content have to be within a specific range. Thus, these challenges have to be overcome prior to presenting forest biomass as a viable feedstock for energy production.

A method to overcome this challenge of quality is through incorporating a terminal in the bioenergy supply chain. A terminal can be a location where biomass is treated to improve its quality to a level specified by the customers (kons et al. 2014). Furthermore, terminals allow the supply chain to adapt to seasonality and uncertainty in regard to both supply and demand. However, a terminal adds a significant cost to a supply chain with already low profit margins (Palander and Voutilainen 2013). Thus the problem is to ensure that the added value to the supply chain outweighs the cost of incorporating a terminal. As such, the key factors that influence the success of incorporating a terminal must be identified. Subsequently, these factors must be considered in the decision-making process of choosing a terminal. Once executed, such a decision is not easily reversible as a terminal requires a considerable amount of investment (Dramm et al. 2004). Thus, the objectives of this study are to:

1. Determine the most important factors that need to be taken into consideration in choosing a terminal for a bioenergy supply chain.
2. Propose a decision-making framework that takes into consideration the different factors to help choose a biomass terminal.

Method

The proposed decision making framework for selecting a forest biomass terminal is illustrated in Figure 1. A combination of two processes are used to evaluate the potential terminals: analytical hierarchy process (AHP) and mixed-integer programming (MIP).

AHP is used to evaluate qualitative information while the MIP model evaluates quantitative information to find the lowest cost solution (Boukherroub et al. 2015b). The output of the AHP procedure is a score for each of the terminal in consideration. The terminals are then ranked based on these scores. The output of the MIP model is the expenditure associated with using a particular terminal for biomass procurement. As such, the scores of the AHP procedure reflect the benefits associated with the different terminals, while the costs are determined by the MIP model. In the result evaluation phase, an analysis is carried out to identify the terminal with the highest benefit-cost ratio.

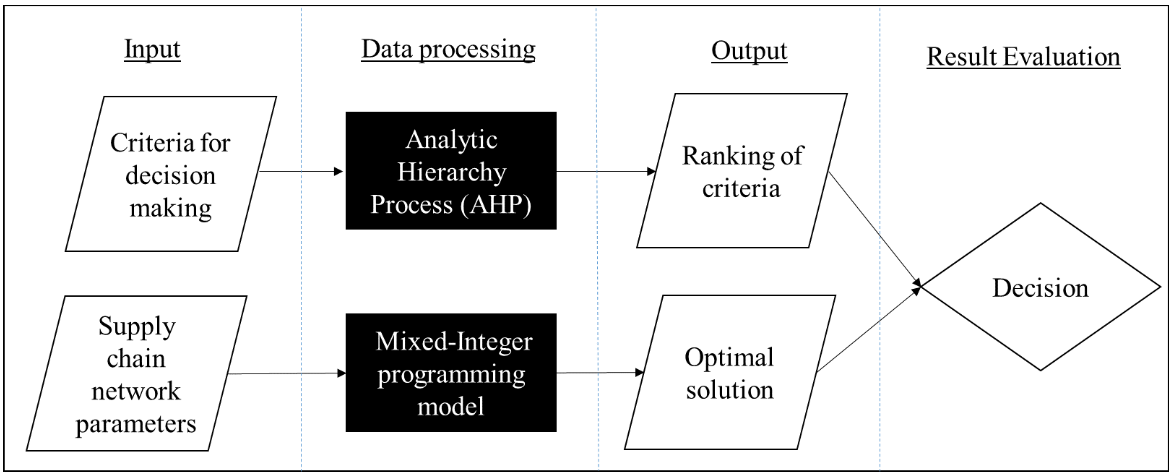

Figure 1. Decision-making framework for terminal selection in the bioenergy supply chain.

A literature review was conducted to select the criteria for terminal selection. The literature search focused strictly on studies conducted on forest biomass terminals. Documents with significant contribution in the criteria selection procedure included Hampton (1981), Dramm et al. (2002, 2004), Kons et al. (2014) and Robichaud (2014). The AHP procedure is conducted on the criteria identified. The mixed-integer programming model representing the bioenergy supply chain was coded in AMPL. The structure of the model is illustrated in Figure 2. The objective function of the multi-period model is to minimize cost while fulfilling all demand from the customers. The decision variables of the model are a) the volume of biomass to be transported in each of the periods, and b) the volume of biomass to be stored in inventory in each of the periods. The constraints included 1) limitation on the availability of biomass in the forests, 2) inventory capacity in the terminals, 3) flow conservations constraints, 4) quality specifications of the customers, and 5) non-negativity and binary constraints. The model takes into consideration the fluctuation in moisture content as biomass flows through the network. It is assumed that once a tree is harvested, its moisture content gradually reduces to the fibre saturation point, then fluctuates with the relative humidity of the air.

The decision making framework was applied to the case of a company in Quebec that recently signed agreements with a number of customers to supply biomass. The company procures biomass from a public forest. As such, inventory data was obtained from the official government reports. The volumes of biomass available for the bioenergy supply chain were subsequently determined using an allometric equation. Information on potential customers and the quantity demanded by period were obtained from the company. Information on distances were extracted using a GIS software. Other model parameters required for the MIP model were obtained from the company. There were four potential sites identified by the company for operating a terminal. The decision-making framework presented in Figure 1 was implemented to make a choice among the four sites.

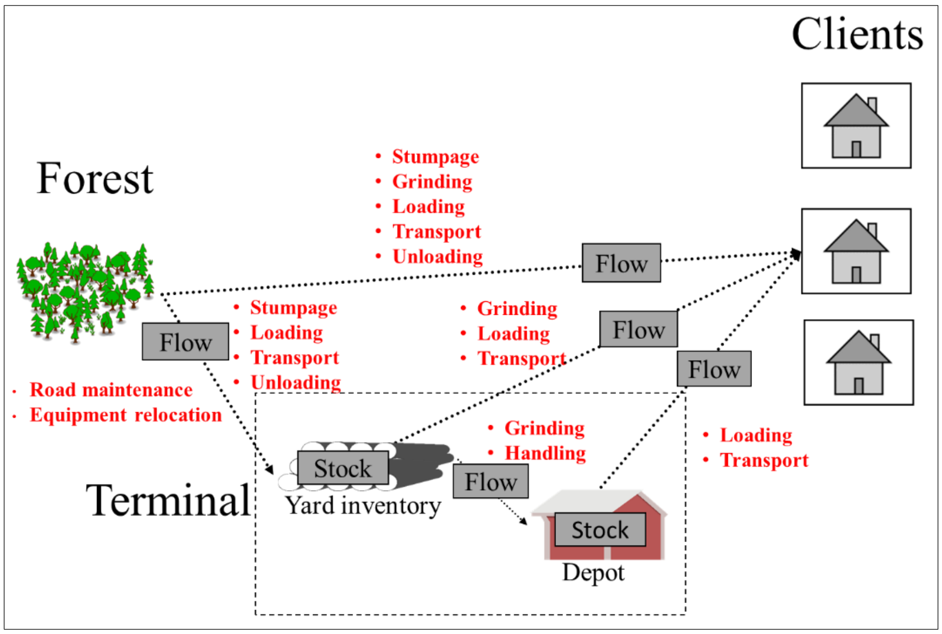

Figure 2. An illustration of the supply chain network modelled using a mixed integer programming formulation. Model parameters are presented in red text, and decision variables are inside the shaded boxes.

Results

The following criteria were identified as input for the AHP procedure:

1. Terminal setup: Terminal setup relates to the total area, shape, location and aspect of the site in consideration. Total area dictates the congestion level and the ease of carrying out daily operations in the terminal. It can also be a limiting factor in future expansion plan. The shape of the terminal will also impact the ease of operation, potentially impacting handling costs. Location and aspect has an impact on the wind pattern and exposure to sunlight. These factors will be important for improving biomass quality.
2. Proximity to forest products manufacturers: Although the primary feedstock source is the surrounding forests, having forest products manufacturers in the vicinity can offer a cheaper option on supply. In some instances, the by-products may have already been dried, providing additional advantage. Also, a terminal in close proximity to other forest products manufacturers could mean biomass procurement costs could be lowered through resource sharing.

3. Infrastructure in place: At a minimum, a terminal will require a balance to measure biomass, a shed to protect biomass from precipitation, a paved area to place the biomass so that dirt does not get mixed in with the feedstock. Investment will need to be made to install these infrastructures if they are not already in place.
4. Access to services: Access to electricity, gas, water, and sewage will be needed to ensure effective and safe working environment. This criterion includes other factors such as distance from hospital, fire and police station.
5. Labour availability**:** Successful operation of the terminal will depend on availability of skilled work force. In certain rural areas availability of labour may be scarce while in other areas it may not be an issue.
6. Proximity to railroad: Truck is usually the primary mode of transportation. However, if growth is planned for the future, access to rail network will be essential to improve efficiency in transportation.

Additional criteria were identified, e.g. closeness to customers, closeness to wood supply, government subsidies. However, these criteria will have a direct effect on the cost. Any criteria that can be measured in terms of its cost will be taken into consideration by the MIP model. Thus, these criteria were not included in the AHP procedure.

The first step of the AHP process was to generate the relative ranking of the different criteria. This was generated through a pairwise comparison. This process involved the chief of operations for the company interested implementing a terminal. The results of this exercise is shown in Table1. For this particular case, it was found that proximity of forest products manufacturers was the most important criterion followed closely by terminal setup. On the other hand, proximity to railroad was judged to be the least important factor.

Table 1: The relative ranking of terminal selection criteria.

Criteria	Eigenvector
Terminal setup	0.2736
Proximity of forest products manufacturers	0.2845
Infrastructure in place	0.0932
Access to services	0.1415
Labour availability	0.1463
Proximity to railroad	0.0607

Next, a pairwise comparison of the terminals was made for each criteria. This exercise generated a ranking of the terminals under the 6 criteria. This matrix of eigenvectors was subsequently multiplied by Table 1, generating a relative ranking of the different terminals in consideration (Table 2, column 2). Based on this result, Site 1 was found to be the most interesting location for operating a terminal, followed closely by Site 3. The next stage included incorporating the results of the optimization model in the decision-making process. The results of the MIP model are presented in Table 2, column

3. For each terminal, the cost represents the yearly expenditure incurred in fulfilling demand. Based solely on the cost, Site 3 would be the preferred location for operating a terminal, followed by Site 1.

Table 2: Each terminal's relative ranking and annual operating costs obtained using the mixed-integer programming model.

Site	Eigenvector	Cost ($)
1	0.3208	317490
2	0.1281	367343
3	0.3130	297493
4	0.2380	316304

In the final step of the procedure, the cost was normalized and benefit-cost ratio was calculated for each terminal. The normalization of the cost was done by summing the costs and determining the contribution (ratio) of each terminal. The benefit-cost ratio was subsequently obtained by dividing the eigenvectors of the terminals (Table 2, column 2) by the normalized costs. Site 3 displayed the highest benefit-cost ratio (1.37) followed by Site 1 (1.31), Site 4 (0.98) and Site 2 (0.45).

Discussion and conclusion

In the initial phase of this project an optimisation model was proposed to help the company select what was deemed the "optimal" location. The company's representative was not convinced as he felt some key criteria were not accounted for. The optimisation model was then combined with a multicriteria technique. This new process was well accepted.

Our proposed framework serves as a convenient and effective tool for practitioners in making a choice on a terminal. The framework allows both qualitative and quantitative information to be taken into consideration in the decision-making process. Using only one of the method (either AHP or MIP) could have lead to a suboptimal decision. As an example, the solution of the AHP procedure would have led to the decision-maker recommending Site 1. However, incorporating the results of the mixed-integer programming model led to a different choice (Site 3). Once executed, the decision cannot be reversed without severe financial repercussions. These terminals require investments ranging from several hundred thousand dollars to millions. A suboptimal decision at this point could lead to a poor performance and inconvenience for many years into the future (Kons et al. 2014).

The application of the proposed framework to a case study demonstrated that the decision to locate a terminal even with a MCDM is not trivial. Although the recommendation for the decision-maker was to choose site 1, others may need to be evaluated. It was clear that sites 1 and 3 were superior to sites 2 and 4. However, the distinction between sites 1 and 3 is not as clear. In fact, a slight change in the pairwise comparison could easily lead to recommendation of Site 3. In such close situations, it is recommended that additional criteria be considered to obtain scores with greater differences. This study was carried out from the perspective of a company, as a result, the criteria developed present the companies' viewpoint. Developing environmental and social criteria may lead to a different ranking of the potential terminals as in Boukherroub et al. (2015b). As such, the results of the framework must be viewed as a strong recommendation rather than the optimal solution.

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Comparing Productivity and Costs of Two Beetle-killed Stand Harvesting Methods in Northern Colorado

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Abstract

There has been increasing interest in utilizing beetle-killed biomass for bioenergy and bio-based products in the Rocky Mountain region of the United States. However, the conventional harvesting method in the region leaves tops and limbs of felled trees on the forest floor or puts them into small in-woods slash piles for later burning, preventing collection of logging residues and non-merchantable parts of beetle-killed trees. This study was designed to introduce a whole-tree harvesting method and compare the productivity and cost of the whole-tree method with the conventional "lop and scatter" method. We conducted a detailed time study on a clear-cut operation of a beetle-killed stand in northern Colorado using the two harvesting methods. Both methods involved the same ground-based machines and operators for a fair comparison, but had a different system configuration as log processing occurred in different locations (i.e., at the stump vs. landing). The results show that the timber production costs of the two methods were \$26.93 per bone dry ton (BDT) for lop and scatter and \$24.80 BDT^{-1} for the whole-tree method. As the bottleneck machine, delimber was the main cause of the higher production cost in the lop and scatter method.

Keywords: mountain pine beetle, whole-tree harvesting, logging residues, detailed time study

Introduction

Beetle-killed trees resulting from the widespread bark beetle infestation in the Rocky Mountain region of the United States represents a vast, high-density biomass feedstock resource for bioenergy and bio-based products. Approximately 1.37 million hectares of coniferous forests in Colorado have been affected by eruptive populations of bark beetle since 1996 (Colorado State Forest Service 2016). Using biomass for bioenergy from the widely available resource of dead pines in the region has become a topic of interest for land managers, but there exist many uncertainties with respect to the harvest of dead trees and their utilization.

In Colorado, a "lop and scatter" method has been widely used for salvage harvest of beetle-killed trees (Matonis et al. 2014). In the method, delimbing and bucking occur at the stump, resulting in tops and limbs being left on the forest floor. This slash retention prevents collection of logging residues for utilization for bioenergy or bio-based products. A whole-tree harvesting method may

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be an alternative option for beetle-kill salvage harvest, which allows for the collection of logging residues at the landing without additional biomass collecting process. Compared to lop and scatter, the whole-tree method could improve delimber efficiency as the machine does not need to move around between log piles in the harvest unit. However, a relatively low productivity in primary transport of whole trees could lead to a higher harvesting cost especially when a system productivity is highly influenced by a long skidding distance (Han et al. 2004, Adebayo et al. 2007).

There has been an information gap about the productivity and costs of beetle-kill salvage harvest, as well as how stand and operational conditions affect the productivity of the two harvesting methods. This study was aimed to analyze and compare the two beetle-kill salvage harvesting methods for their productivity and costs through a detailed time study. In collaboration with the Colorado State Forest Service and our industry partners, we applied the two methods side by side on the same beetle-killed forest stand located in the Colorado Forest State Park. Our detailed methods and study results are presented below.

Methods

Study site and harvesting methods

A 10.1-acre lodgepole pine (*Pinus contorta*) stand was selected as our study harvest units. The stand is located in the State Forest State Park in northern Colorado (40°57´N, 105°98´W), and has been infested by the mountain pine beetle since 2008. The stand located on a relatively flat terrain was divided into two approximately equal size harvest units for side-by-side application of the two harvest methods: lop and scatter, and whole-tree harvesting (Figure 1). The units were cruised prior to harvesting using a systematic sampling method with a 5% of sampling intensity. Trees larger than 5 inch diameter at breast height (DBH) and their individual mortalities were recorded and used to describe pre-harvest stand characteristics (Table 1).

Table 1. Stand characteristics of the study harvesting units.

Characteristics	Harvesting unit	
	Lop and scatter	Whole-tree harvesting
Area (ac)	5.3	4.8
Mean DBH (in)	8.8	8.8
Mean height (ft)	60.1	64.2
Average basal area (ft^2/ac)	145.0	150.6
Trees per acre	331	350
Mortality (%)	39.5	47.3

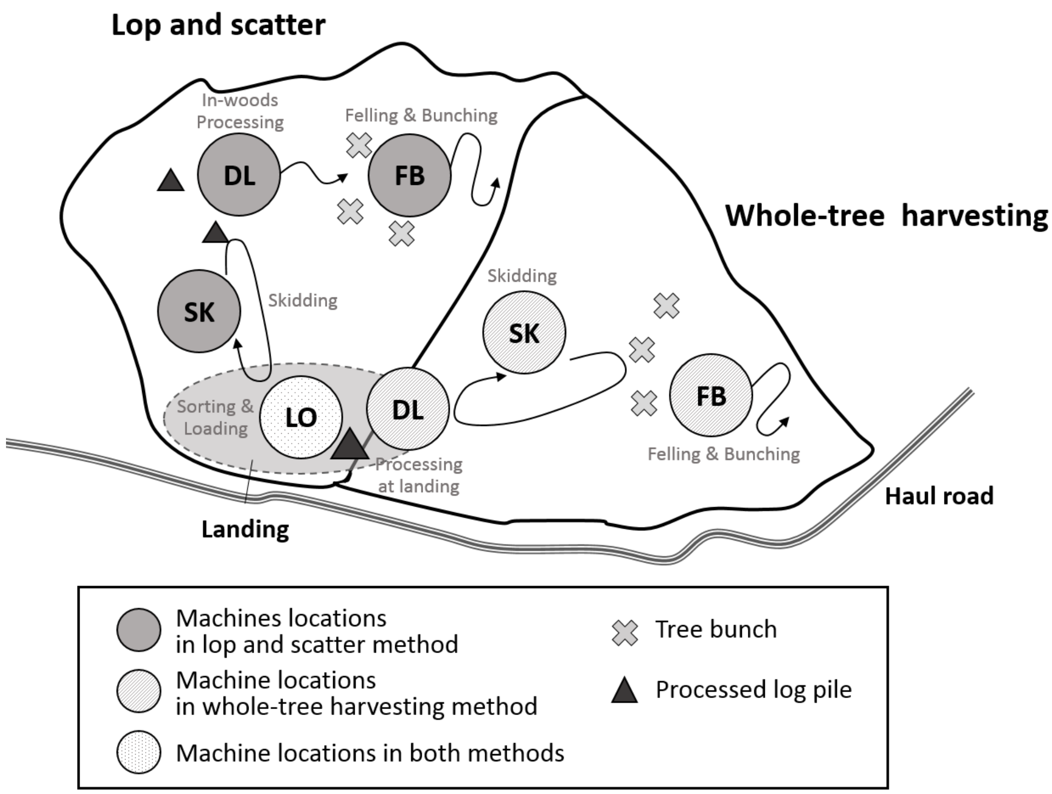

Figure 1. A map of the study harvest units showing harvesting machines and processes involved in each harvesting method.

Each unit was clear-cut with the same ground-based machines and operators for a fair comparison, but had a different system configuration as log processing occurred in different locations (i.e., at the stump vs. landing). In the lop and scatter method, a TimberPro TL-735-B feller-buncher was used to cut and bunch trees at the stump. Two Timberline SDL2 stroke delimbers then top, delimb and buck trees prior to primary transport (skidding) of logs carried out by a Tigercat 615C skidder (Table 2). In the whole-tree method, the skidder brought whole-trees to the landing where delimbers process the trees while creating slash piles at the landing. For both methods, a Barko 495ML Magnum loader was used to sort and load logs onto log trucks.

Table 2. Harvesting equipment purchase prices, utilization rates and machine rates used in the study.

Machine (make/model)	Purchase price	Utilization rate[a]	Machine rate
	($)	(%)	($/SMH[b])
Feller-buncher (TimberPro TL-735-B)	395,000	60	134.04
Stroke delimber (Timberline SDL2)	355,000	65	114.69
Skidder (Tigercat 615C)	219,000	60	90.97
Grapple loader (Barko 495ML Magnum)	205,000	65	79.26

[a] Adapted from Brinker et al. (2002)
[b] Scheduled machine hour

Data collection and analysis

Detailed time study data were collected to estimate machine productivity and costs using standard work study techniques (Miyata 1980, Olsen et al. 1998, Brinker et al. 2002). Delay-free cycle times for each machine were recorded using stop watches. Independent variables hypothesized to have an influence on machine productivity were also measured and recorded for each cycle (Table 3). Predictive equations were developed using ordinary least squares regression techniques. Travel distances of feller-buncher were estimated by ocular measurement. The empty travel and loaded travel distances of skidder were measured using GPS receivers (Columbus VGPS-900) mounted on the skidder.

For the feller-buncher cycle time equation, we merged data from both units to develop a single cycle time regression equation as there was no difference in feller-buncher operations in both units. However, we developed separate equations for delimber cycle times because the lop and scatter method required the delimber to move from pile to pile, whereas the delimber stayed at the landing in whole-tree harvesting. An indicative variable was used to identify the delimber movement in each cycle for lop and scatter (Table 3). Two different cycle time equations were also developed for skidding operation as the skidder handled a different type of product (i.e., processed logs vs. whole-trees) in each method. For loader cycle times, we developed a single cycle time equation for both methods with an indicator variable for two different activities (0 = sorting, 1 = loading). All statistical analyses were conducted in R software (R Development Core Team 2014), and values of $P < 0.05$ were considered to be statistically significant.

The amount of production was normalized to bone dry tons (BDT) by applying a wood density of 0.41 BDT per m^3 (Miles and Smith 2009) to the average log volume estimated from field data samples. Using the average cycle time and the average production per cycle, machine productivity was estimated in BDT per scheduled machine hour (SMH). A bottleneck machine was identified, and the entire system productivity was determined using the bottleneck productivity, assuming all the machines work simultaneously in a ‘hot’ operation.

Results

Table 3 shows delay-free cycle time regression equations developed for individual machines involved in the two harvesting methods. For feller-buncher, the number of standing trees including both live and dead, the number of downed dead trees, and travel distance of machine per each cycle are significant predictors for the machine cycle time. There were no effects of tree mortality between standing live and standing dead trees on feller-buncher cycle times, but handling downed dead trees has a significant effect on cycle times. For delimbers, both the number of live and dead trees are significant predictors of the cycle time and it appears that it takes relatively less time to process dead trees than live trees in both methods. In the lop and scatter unit, the number of logs, and empty and loaded distances are significant variables in the regression model. In whole-tree harvesting, loaded distance is a significant variable. The number of logs and activities are significant predictors of cycle time for grapple loader.

Table 3. Delay-free cycle time (minute) regression models for feller-buncher, delimber, skidder, and grapple loader used in lop and scatter and whole-tree harvesting.

Machine	Parameter	Estimate	SE	*t*	*Pr*	Model adj. R^2
Feller-buncher	Intercept	8.866	0.646	13.73	<0.01	0.4707
	No. of standing trees	4.207	0.311	13.54	<0.01	
	No. of downed trees	14.229	0.931	15.28	<0.01	
	Travel distance (ft)	0.307	0.023	13.36	<0.01	
Stroke delimber	Intercept	32.089	2.116	15.16	<0.01	0.3369
(lop and scatter)	No. of live trees	5.999	1.261	4.76	<0.01	
	No. of dead trees	4.754	1.774	2.68	<0.01	
	Move and reposition (MR)	29.184	2.486	11.74	<0.01	
Stroke delimber	Intercept	32.183	1.493	21.551	<0.01	0.1693
(whole-tree harvesting)	No. of live trees	5.723	0.825	6.938	<0.01	
	No. of dead trees	5.294	0.971	5.452	<0.01	
Skidder	Intercept	54.787	21.972	2.49	<0.05	0.7295
(lop and scatter)	No. of logs	2.491	1.043	2.39	<0.05	
	Empty distance (ft)	0.076	0.019	4.00	<0.01	
	Loaded distance (ft)	0.202	0.050	4.04	<0.01	
Skidder	Intercept	5.952	64.725	0.09	0.93	0.5271
(whole-tree harvesting)	No. of trees	1.796	1.763	1.02	0.32	
	Empty distance (ft)	0.163	0.126	1.30	0.21	
	Loaded distance (ft)	0.236	0.104	2.28	<0.05	
Loader	Intercept	23.939	1.958	12.228	<0.01	0.1801
	No. of logs	3.430	0.482	7.120	<0.01	
	Activity type	9.248	1.895	4.881	<0.01	

The standardized cycle times estimated using the cycle time regression models show that feller-buncher and grapple loader have the same productivities in both methods (Table 4). However, the productivity of two delimbers used in both methods is different. The productivity of delmber in the lop and scatter method is 20.68 BDT of timber per SMH, 8% lower than that in the whole-tree method mainly due to frequent movements of machine in the lop and scatter method. Another difference in individual machine productivities in the two methods occurs during skidding operation. The productivity of skidder is 25.74 BDT SMH^{-1} for the lop and scatter method, whereas the trees are transported to the landing at a rate of 25.07 BDT SMH^{-1} in the whole-tree method. Delimber is turned out to be the bottleneck machine in both methods.

Assuming that the two harvesting methods are applied as a ‘hot’ operation, the unit cost of timber production is \$24.80 BDT^{-1} in the whole-tree method, which is 8% lower than the lop and scatter method. This difference is mainly caused by a higher productivity of delimber in the whole-tree method (Table 4).

Table 4. Productivity and costs of the lop and scatter, and whole-tree harvesting methods

Configuration/machine	Machine		System	
	Productivity	Cost	Productivity	Cost
	(BDT SMH^{-1})	(\$ BDT^{-1})	(BDT SMH^{-1})	(\$ BDT^{-1})
Lop and scatter				
Feller-buncher	27.76	4.83	20.68	26.93
Stroke delimber*	20.68	5.55		
Skidder	25.74	3.53		
Grapple loader	26.31	3.01		
Whole-tree harvesting				
Feller-buncher	27.76	4.83	22.45	24.80
Skidder	25.07	3.63		
Stroke delimber*	22.45	5.11		
Grapple loader	26.31	3.01		

* Estimated for two delimbers

Conclusion

Our detailed time study on beetle-killed stand harvesting in northern Colorado suggests that downed dead trees may significantly increase feller-buncher cycle times compared to standing trees. On the contrary, processing dead trees using a stroke-delimber appears to take slightly less time than processing live trees. Our comparisons of the conventional lop and scatter method with whole-tree harvesting in the study harvest units indicate that whole-tree harvesting could be more cost-effective in timber production while allowing for the collection of logging residues at the landing. Major differences in productivity occurred during delimbing and skidding. This potential gain from whole-tree harvesting by lower costs may help improve the economic feasibility of utilizing low value forest residues for bioenergy and bio-based products. Future studies should further analyze the potential gains and losses in applying whole-tree harvesting under a wide variety of stand and operational conditions.

Acknowledgments

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