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Title: The Effect of Downed-trees on Harvesting Productivity and Costs in Beetle-killed Stands.

Abstract approved:

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Woodam Chung

The mountain pine beetle has impacted over 5 million hectares of pine forests in the Rocky Mountains region in the United States. Although some beetle-killed stands are available for salvage harvesting, there are many uncertainties in harvesting beetle-killed stands including safety, costs, recoverable products and their values. These uncertainties impose limitations on the ability of land managers to make timely decisions regarding beetle-killed stand management. This study aimed to quantify the difficulty of harvesting operations in beetle-killed forest stands with various downed-tree proportions. A detailed time study was conducted on a whole tree clear-cut harvest using a ground-based system in western Montana in August 2015. The effects of downed-trees on machine productivity and cost were analyzed using the collected field data. Our results indicated that tree conditions, including standing or down, not only significantly affected the productivity of the feller-buncher, but also affected the unit costs and productivity of the entire harvesting system, changing of the bottleneck machine in a combined felling, skidding and delimbing operation. This research also provided insight into how optimized system configuration may help cope with the increase of harvesting cost caused by the temporal changes in beetle-killed stand

conditions, allowing forest managers and practitioners to understand the potential impact of delayed stand management decisions on harvesting costs and outcomes.

The Effect of Downed-trees on Harvesting Productivity and Costs
in Beetle-killed Stands

by

Yaejun Kim

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Yaejun Kim, Author

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1. Introduction

The recent outbreak of the mountain pine beetle (*Dendroctonus ponderosae*) has affected a large area of forests in North America. In affected stands, successful beetle brood development is accompanied by extensive tree mortality. The mountain pine beetle has caused widespread tree mortality in almost 18.3 million hectares in British Columbia, Canada (Corbett et al. 2015) and also affected 4 million ha of trees in the Rocky Mountain region in the United States as of 2014 (USDA Forest Service 2015). The large accumulation of dead trees has become an increasingly complex forest management issue, presenting a serious challenge to forest managers and practitioners.

Mountain pine beetles usually attack lodgepole pine trees by laying eggs that hatch into larvae under the bark, which also introduces a blue stain fungus to the trees (Robinson 1962). The fungus and larvae feeding on the tree kill the live tree by interrupting nutrient and water transport (Gibson et al. 2009). After the tree is dead, it loses its firmness due to bole decay and eventually falls on the forest floor, changing the stand structure (Mitchell et al. 1998, Shore et al. 2006). Major structural changes in even-aged lodgepole pine stands include steep declines in stocking and increases in understory vegetation and down wood, among other altered stand conditions.

Depending on site conditions and ownership objectives, it is often deemed beneficial to harvest dead trees in infested forests because beetle-killed trees may be still utilized for various forest products, including lumber, pulp, and bioenergy (Hu et al. 2006, Chow et al. 2007, Pan et al. 2008, Kumar 2009, Zacher et al. 2014). Such harvests are called salvage harvests, and are focused on salvaging economic value, though they may have other beneficial impacts on fire risk and regeneration. Most beetle-killed lodgepole pine trees can be used for sawlogs if there are no severe grade or scale defects, such as checking and rot (Lewis et al. 2006, Orbay et al. 2006). Dead trees can be also utilized for pulpwood (Hu et al. 2006), and sometimes for aesthetic wood products because of the unique pattern left by larvae feeding and blue stain. In addition, given increasing recognition of the social and environmental values of biomass energy and bio-based products (Anderson et al. 2012), beetle killed biomass has been recently studied as a feedstock source for such products (Kumar et al. 2008, Akhtari et al. 2014).

Harvesting of beetle-killed stands could be also advantageous in terms of stand regeneration and management of fuel loads. Lodgepole pines are regarded as valuable species for timber production (Gara et al. 1985). Without salvage harvesting, lodgepole pine forests would be likely to have more subalpine fir which is not preferred for timber (Vyse et al. 2009, Collins et al. 2011). Furthermore, dead trees could substantially increase fuel loading in the forest, causing changes in fire behavior and therefore increasing fire risks, especially with regards to high fire intensity and subsequent site impacts (Jenkins et al. 2008, Collins et al. 2012, Hicke et al. 2012).

Thoughtful harvesting system design is essential for successful harvesting operations in any forest stand from economic, environmental, and safety perspectives. Various factors related to stand characteristics, terrain conditions and road infrastructure should be taken into account in harvest unit and system design to maintain high productivity and lower production costs (Kellogg et al. 2004, Bolding et al. 2009). Although there have been many studies concerning the performance of different harvesting systems under a variety of stand and terrain conditions (Wang et al. 2004, Bolding et al. 2009), there is no study that has specifically looked at beetle-killed stand harvesting operations with the existence of a wide range of downed trees. This research is needed to quantify the difficulty of harvesting in beetle-killed stands with the existence of downed-trees in order to fill the existing information gap and guide successful harvesting operations. This will also provide forest managers and practitioners with insights about how downed-trees caused by the mountain pine beetle mortality can affect the performance of harvesting equipment and systems, allowing system design improvement. Furthermore, the work provides a better understanding of the operational costs of delaying harvest in stands.

This study addressed the effects of the existence of downed-trees in beetle-killed stands on harvesting costs and productivity. We conducted a detailed time study on beetle-killed lodgepole pine harvesting in western Montana on a stand that was clearcut using a ground-based whole-tree mechanized harvesting system. The study was intended not only to develop a new cost prediction model for beetle-kill stand harvesting, but also to provide useful insights about how downed-trees in beetle-kill stand conditions may change the optimal harvesting system configuration, allowing forest managers and practitioner to identify current barriers and improve opportunities and outcomes.

1.1 Objectives

The specific objectives of this study were to:

1. Quantify the effects of downed-trees on the performance of individual harvesting equipment.

2. Develop predictive cost and productivity models for whole-tree mechanized harvesting system applied to beetle-killed stands with various downed-trees proportions.

3. Demonstrate the utility of the predictive models in harvesting system configuration to improve system productivity based on the proportion of downed-trees.

2. Literature Review

Estimating timber harvesting costs is an essential process for successful harvesting practice (Han 2004, Bolding et al. 2009). Timber harvesting cost and productivity models allow forest practitioners not only to estimate harvesting costs and compare different harvesting options (Légère et al. 1998, Baker et al. 2010, Anderson et al. 2012), but also to configure a cost-effective harvesting system for given terrain and vegetation conditions (Li et al. 2006, Ghaffariyan et al. 2013).

Timber harvesting machine productivity largely depends on production and delay times, as well as interactions among machines in the system (Ovaskainen et al. 2004). Various types of time studies (i.e., shift-level, activity sampling and detailed time study) have been widely used in the forest industry to assess harvesting production rates of individual machines and the entire system (Howard 1989). Time study is “a technique used to establish a standard time for a job or for an operation” (Telsang 2006). A detailed time study, which collects production cycle times and the production rates of individual machines, as well as influencing factors, allows one to develop regression models that can be used to predict average machine productivity within the proper range of site conditions (Olsen et al. 1983). When combined with machine rate calculations, the productivity models can be also used to estimate the unit production costs of individual harvesting machines.

Predictive regression models for productivity also provides an opportunity to identify and evaluate influential factors for the performance of harvesting machines and thus of the entire harvesting system (Howard 1989). A bottleneck machine or function can be also identified when machine interactions are unavoidable or systems are unbalanced, based on the models.

Many previous time studies have examined the effects of numerous variables on the performance and productivity of timber harvesting machines (Table 1). Those variables are related to forest stand characteristics, terrain conditions, and human factors (Kellogg 1992). Tree size is one of the influential factors on harvesting productivity, occasionally described as the average tree volume (Lanford et al. 1996, Nurminen et al. 2006, Nakagawa et al. 2007). The moving distance of individual machines is also associated with the harvesting productivity, increasing cycle time of machines that cover larger distances and decreasing productivity as a result (Kluender et al. 1997, Jiroušek et al. 2007). The number or weight of trees in one cycle of machine operation (e.g., turn payloads) is also a major variable in the productivity of the harvesting operations (Kellogg et al. 2004, Pan et al. 2007). Furthermore, productivity varies considerably with the experience and skill of machine operators (Richardson et al. 1994, Purfürst et al. 2011), indicating that human factors also have a large influence on harvesting operations (Kirk et al. 1997, Kärhä et al. 2004).

Table 1. Influential variables on the productivity of ground-based harvesting machines identified from the past time studies.

Machine	Variables	Remark	References
Feller-buncher	DBH		(Adebayo et al. 2007)
	Basal area		(Lanford et al. 1996)
	Distance between trees		(Li et al. 2006)
Harvester	DBH / tree volume		(Lanford et al. 1996)
	Direction (uphill)	Binary variable	(Adebayo et al. 2007)
	Opening[1)]	Binary variable	(Kellogg et al. 2004)
	Hang-up	Binary variable	
Skidder	# of trees		(Pan et al. 2007)
	Payload		(Li et al. 2006)
	Travel distance (empty, loaded)		(Pan et al. 2007)
	Direct (uphill)	Binary variable	(Adebayo et al. 2007)
Forwarder	# of logs / # of products		(Kellogg et al. 2004)
	Payload		(Li et al. 2006)
	Travel distance (empty, loaded)		(Adebayo et al. 2007)
	Direction (uphill)	Binary variable	
Processor	DBH / tree volume		(Adebayo et al. 2007)
	# of logs		
Loader	# of logs		(Pan et al. 2007)
All	Operator skills		(Richardson et al. 1994)
	Silvicultural treatments		(Kellogg et al. 2004)

1) In thinning treatment

Although many studies have already addressed harvesting productivity and costs for typical timber harvesting operations under a variety of site conditions (Kellogg 1992), no study has so far looked at beetle-infested stand harvesting with a mix of standing and downed-trees. The existence of downed-trees in a beetle-killed stand is expected to hinder the machine operation and require additional movement and time of machines. The conventional wisdom of loggers generally supports this hypothesis, but the actual effects on operations have not been studied nor empirically quantified. Because the intrinsic characteristics of beetle-killed stands might substantially affect the cycle time, and therefore the productivity of harvesting machines and production costs, it should be properly accounted for in predictive productivity and cost models for accurate and realistic estimation of harvesting costs in beetle-killed stands.

Johansson et al. (2002) reported that multiple tree-cutting in a cycle is more productive for a feller-buncher than a single-tree cutting. When it comes to beetle-killed stands, the stock of downed and hung-up trees may reduce the frequency of multiple tree cutting with a feller-buncher, as well as reduce machine maneuverability within the stand, resulting in a lower machine productivity compared to similar operations in a live stand. Kellogg et al. (2004) reported that hang-up trees lead to additional machine head-movements for handling, and therefore result in decreased machine productivity. Similarly, collecting downed trees can cause inevitable tree-handling difficulties for harvesting machines because it requires additional machine-head tilting and the caution of the operator not to hit the ground with the machine head. Additional cycle time due to harvesting difficulties in such stands would be increased if the operator is new to or less experienced in beetle-killed stand harvesting (Purfürst et al. 2011).

The unique characteristics of beetle-killed forest stands with widespread down trees can affect the productivity and costs of harvesting equipment and system as a whole. This study attempted to address the effects of the existence of downed-trees on harvesting costs and productivity for beetle-killed stand harvesting operations. In order to develop cost prediction models, a detailed time study method were applied to a whole-tree clear cut with a ground-based mechanized system in western Montana. The time study data were statically analyzed to address the effects of downed-trees on individual machine performance, bottleneck function and the productivity and costs of the entire harvesting system. Results are examined to provide potential solutions to the operational challenges associated with harvesting these stands.

3. Materials and Methods

3.1 Study Site and Harvesting System

The study harvest unit was a 27-acre mixed conifer stand on a gentle slope located in the northwest of Chessman Reservoir (46° 28' N, 112° 11' W) in western Montana (Figure 1). The dominant tree species was lodgepole pine (*Pinus contorta*), and the stand had been infested by mountain pine beetles since 2008 (Table 2). Pre-harvest stand inventory data were collected using Lund's methods (Lund et al. 1989) to provide unbiased sampling plot locations throughout the harvesting unit. A total of 18 sampling plots were established with 5% sampling intensity, using a grid of equilateral triangles on harvesting unit.

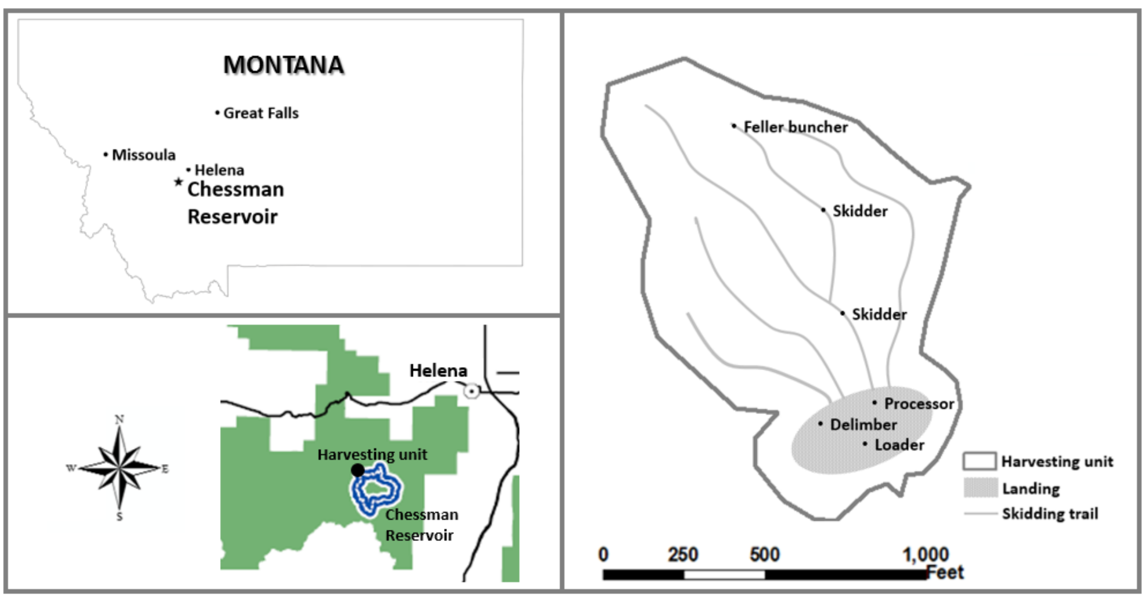

Figure 1. Site map showing the harvesting unit.

Table 2. Vegetative characteristics of the study harvesting unit

Characteristics	
Total area (ac.)	27.0
Average DBH (in.)	6.6
Average height (ft.)	42.9
Average basal area (ft^2/ac.)	42.8
Trees per acre	180.0
Beetle-infested year	2008
Tree condition proportion (%)	
- Standing trees	78.0
- Downed trees	22.0
Species proportion (%)	
- Lodgepole pine	91.0
- Douglas-fir	8.8
- Subalpine fir	0.2

A whole-tree clear cut with a ground-based mechanized system was applied to the harvesting unit with six pieces of harvesting equipment including one feller-buncher, two skidders, one processor, one delimber, and one loader (Figure 2). The average slope in the harvesting unit was 8.6 percent. A feller-buncher (Tigercat LX830C with a 5702 saw-head) with a continuous disc-saw was used for felling and bunching. With an average skidding distance of 487 feet, two grapple skidders (John Deere 848H and Caterpillar 535C) were operated simultaneously with the feller-buncher to extract cut and bunched trees to the landing. A stroke boom delimber (Link-Belt 2800 with a Denharco-head) and a processor (Link-Belt 290 with a Waratah 623-head) were used to delimb and process trees into two log sorts: sawlogs, and post and poles. There was one landing location where three machines were operated: a delimber, a processor, and a loader. The John Deere 690E LC loader was used for loading logs onto logging trucks.

All the equipment was operated simultaneously resulting in a “hot” harvesting operation. All the machine operators appeared to be fairly skilled and experienced except for the Caterpillar 535C skidder operator, who was new and training on the job.

Figure 2. Six machines used during the harvesting operation at the study site

3.2 Detailed Time Study and Cycle Time Regression Models

A detailed time study was conducted in August 2015 to collect time and production data of individual harvesting machines. These data were used to develop multiple least-squares linear regression models of delay-free cycle time. The start and end of cycles were defined for individual machine operations (Table 3), and recorded during the field study. Independent variables hypothesized to affect cycle time were also recorded along with each cycle time of the machine (Table 4). Distance of machine movement was measured using a laser rangefinder, and the number of trees per cycle were visually counted. Delays were classified into four categories (i.e., administrative, mechanical, operational, and personal) and identified during the field study. Administrative delays included communications among supervisor and machine operators. Mechanical delays were engine warm up, breakdowns, and parts replacement. Operational delays included brushing, decking and waiting. Personal delays included eating, break, and phone call. If any delay was observed in a cycle, we skipped recording of the cycle and resumed data collection when the next full cycle occurred without a delay.

In order to quantify the effects of downed-trees on the productivity of machines, we classified various tree conditions into two categories: standing and downed. Standing trees were trees that had an unbroken portion of the bole at least 4.5 feet in length from the ground and lean less than 45 degrees from the vertical (Woudenberg et al. 2010). Downed trees were trees that had an unbroken bole of at least 4.5 feet, but were partially or completely detached from the stump leaning more than 45 degrees from the vertical. Trees that were completely downed with full contact with the ground were also counted as downed trees.

Table 3. Definition of machine cycles

Machine	Definition of machine cycle
Feller-buncher	**Starts when moving toward target trees, ends when cut trees are put into a bunch on the ground and the machine is ready for the next cycle.**
Skidder	**Starts when moving from the landing to a tree bunch made by feller-buncher, ends when dropping the bunch at the landing and the machine is ready for the next cycle.**
Delimber & Processor	**Starts when the delimber/processor head moves to grasp trees for processing, ends when processed logs have been stocked and the machine is ready for the next cycle.**
Loader	**Starts when the grapple head moves to grasp logs, ends when the logs have been loaded on a truck and the machine is ready for the next cycle.**

Table 4. Time elements and predictor variables

Machine	Time element per cycle	Predictor variables
Feller-buncher	1. Moving to trees	▪ Travel distance (ft.)
	2. Positioning the felling head and felling (include. grasping downed-trees)	▪ The number of standing trees* ▪ The number of downed trees*
	3. Bunching	▪ Total cycle time
Skidder	1. Travel empty	▪ Empty travel distance (ft.)
	2. Positioning and grappling	▪ The number of tree pieces*
	3. Travel loaded	▪ Loaded travel distance (ft.)
	4. Unloading	▪ Total cycle time
Delimber & Processor	1. Grappling	▪ The number of sawlogs* ▪ The number of post and poles*
	2. Delimbing, processing and sorting	▪ Total cycle time
Loader	1. Grappling	▪ The number of logs*
	2. Loading	▪ Total cycle time

*also used for the production measurement

Collected data from the time study were used to develop delay-free cycle time regression models. Outliers were screened if they were more than 3 standard deviations from the mean. We evaluated data through correlation statistics (i.e., Spearman's rank-order correlation and Pearson's correlation). Pearson' correlation was used to measure the linear correlation between explanatory variables and dependent variable with assumptions of normality, linearity, and constant variance, whereas the Spearman's rank-order correlation was used for the monotonic correlation when the assumptions of the Pearson's correlation does not seem satisfied.

According to the data split method with a single iteration for model validation (Pan et al. 2007), we randomly selected 67% of the data for model training and used the rest of the data (i.e., 33%) for model validation (Figure 3). R-squared values between predicted and observed cycle time were presented for model validations to indicate how close the reserved data are to the regression model (Adebayo et al. 2007).

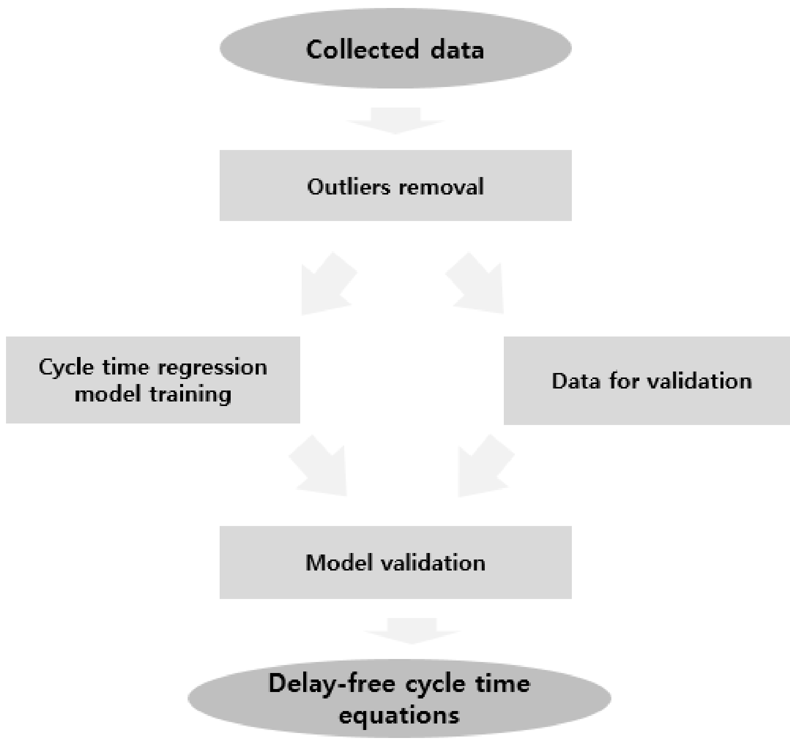

Figure 3. A workflow employed to develop delay-free cycle time equations

3.3 Harvesting System Productivity and Production Cost

The hourly productivity of the harvesting system and the unit cost of timber production were estimated following the step-by-step approach shown in the cost tree diagram (Figure 4). Unit cost in this case is production cost on a mass basis in U.S. dollars per metric ton (\$ t^{-1}). We estimated the individual machine productivity first, and then combined machine productivities together to estimate the productivity and cost of production for the entire harvesting system based on individual machine rates. The machines which had the same roles in timber production can be regarded as the same function of harvesting (i.e., felling and bunching, skidding, processing, and loading), and therefore are interchangeable in the system analysis.

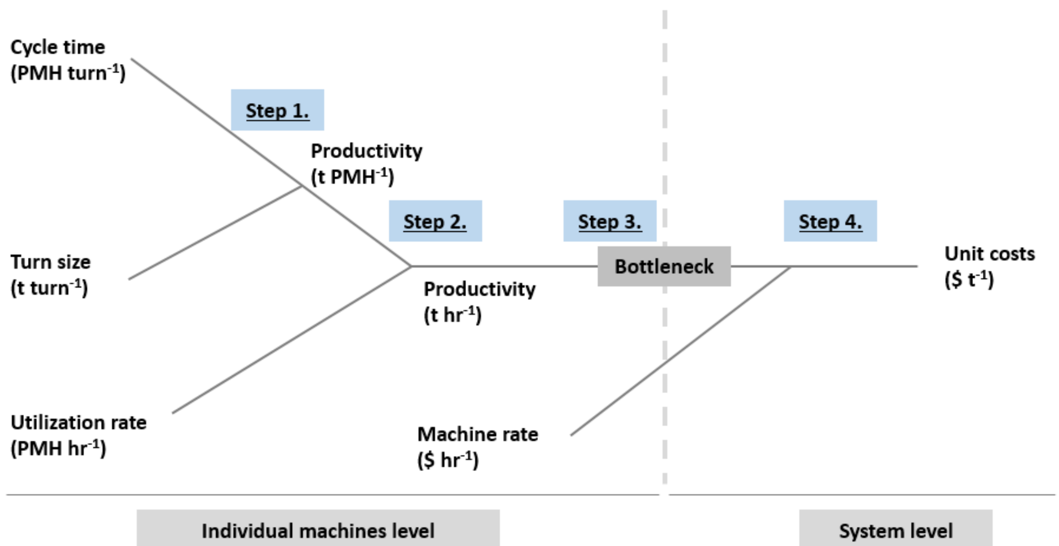

Figure 4. Cost tree diagram used to estimate harvesting system productivity and production costs

Step 1 (per machine):

- $\boldsymbol{Cycle\ time}\left(\boldsymbol{PMH\ turn^{-1}}\right)\ \boldsymbol{is\ estimated\ from\ the\ cycle\ time\ regression\ model}$

- $\boldsymbol{Turn\ size}\ \left(\boldsymbol{t\ turn^{-1}}\right) = \#\ \boldsymbol{of\ trees\ \ or\ logs}\ \times \textbf{average log}\ \boldsymbol{weight}\ (\boldsymbol{t})$

- $\boldsymbol{Productivity\ per\ PMH}\ \left(\boldsymbol{t\ PMH^{-1}}\right) = \frac{\boldsymbol{Turn\ size}\ (\boldsymbol{t\ turn^{-1}})}{\boldsymbol{Cycle\ time}\ (\boldsymbol{PMH\ turn^{-1}})}$

Step 2 (per machine):

- $\boldsymbol{Utilization\ rate}\ (\%) = \frac{\boldsymbol{Productivie\ machine\ hours}\ (\boldsymbol{PMH})}{\boldsymbol{Scheduled\ machine\ hours}\ (\boldsymbol{hr})} \times \mathbf{100}$

- $\boldsymbol{Productivity\ per\ SMH}\ \left(\boldsymbol{t\ hr^{-1}}\right)$

$$= \boldsymbol{Productivity\ per\ PMH}\ \left(\boldsymbol{t\ PMH^{-1}}\right) \times \frac{\boldsymbol{Utilization\ rate}\ (\%)}{\mathbf{100}}$$

Step 3 (for the entire system):

- $\boldsymbol{System\ productivity}\ \left(\boldsymbol{t\ hr^{-1}}\right) = \boldsymbol{Productivity\ of\ the\ bottleneck\ function}$

Step 4 (for the entire system):

- $\boldsymbol{Unit\ production\ cost}\ \left(\$\ \boldsymbol{t^{-1}}\right) = \frac{\boldsymbol{Sum\ of\ machine\ rates}\ \left(\$\ \boldsymbol{hr^{-1}}\right)}{\boldsymbol{System\ productivity}\ (\boldsymbol{t\ hr^{-1}})}$

The average cycle time for the feller-buncher was estimated using the delay-free cycle time regression model based on given explanatory variables (Step 1 in Figure 4). We then estimated the turn size for the cycle by multiplying the number of trees cut and bunched in the cycle by the average log weight produced from a tree in green tons (t). Due to the relatively small diameter and short tree height (Table 2), most of the harvested trees yielded only one 36 foot log per tree, and we estimated the average log weight based on the average number of logs loaded on a truck and the average net weight of truck loads obtained from the mill trip tickets.

We used the field data for the skidding function only from the John Deere 848H because the other skidder, a Caterpillar 535C, was operated by a new, inexperienced operator in training, and was therefore deemed non-representative. Cycle time was estimated using the delay-free cycle time regression model, and the turn size was estimated based on the average log weight and the number of trees carried during the cycle (Figure 4: Step 1).

Similarly, the delay free cycle time regression models provided the average cycle times of the delimber and the processor by taking into account the average number of handled trees in one cycle. The turn size for each machine was also determined by the number of logs in one cycle and the average log weight.

Utilization rate is the ratio of the productive machine hours (PMH) to the scheduled machine hours (Brinker et al. 2002). Scheduled machine hours (SMH) include all time the machine is scheduled to work, whereas productive machine hours represent the time during a machine performs its work without any delays (Brinker et al. 2002). In calculating utilization rates, the machines' unproductive time is the difference between productive and scheduled times which includes delays such as maintenance, repairs, and break. Because delays were not recorded during the field study, we used general utilization rates for individual machines that are described in Table 5. These rates were used in many previous studies to estimate generalized machine productivities while accounting for unknown or irregular delay times, such as machine breakdowns and maintenance (Kellogg 1992, Brinker et al. 2002, Dodson et al. 2015). By applying these utilization rates, we calculated individual machine productivities on a SMH (hr) basis. We then identified the bottleneck function that had the lowest productivity among those employed in the harvesting system (Step 3). The productivity of the bottleneck function was used to determine the entire system productivity. A bottleneck function can be a single machine or multiple machines used for one single function in timber production.

To estimate system production costs, hourly costs of the system are combined with system hourly productivity (Step 4 in Figure 4). For the system cost, the machine rates of individual machines involved in the system were calculated using the standard machine rate calculation method (Miyata 1980). The machine rate is an hourly machine cost and includes machine owning costs, operating costs, and labor costs (Figure 5). Machine purchase prices were obtained from machine dealers and a previous study (Dodson et al. 2015). A labor cost of \$28.58 hr^{-1} was used as the average 2015 Montana base wage for forestry machine operators including fringe benefits (Bureau of Labor Statistics 2015). The diesel cost was assumed at \$2.50 $gallon^{-1}$ (U.S. Energy Information Administration 2016), which was the fuel cost at the time of the study, and the fuel consumptions of individual machines were calculated as a function of machine horsepower (Brinker et al. 2002). Other assumptions included scheduled machine hours per year (i.e., 2000 hours) and different salvage values for each machine after a useful life of 5 years (Table 5).

Table 5. Cost parameter assumptions used for machine rate calculations

	Values				
Machine type	**Feller-buncher**	**Skidder**	**Delimber**	**Processor**	**Loader**
Variable/Model	**Tigercat LX830C**	**JD 848H**	**Link-belt 2800 Denharco head**	**Link-belt 290 Waratah head**	**JD 690E LC**
Purchasing price ($)	500,000	369,444	442,853	513,971	176,666
Horsepower (hp)	300	200	194	177	140
Salvage value (%)	15	15	20	20	30
Economic lives (year)			5		
SMH/year			2,000		
Interest rate (%)			10		
Insurance & taxes (%)	3.5	5.0	2.0	4.0	1.5
Diesel price ($ gallon^{-1})			2.50		
Fuel use rate (gallon hp^{-1} PMH^{-1})	0.0263	0.0292	0.0292	0.0292	0.0217
Lubrication ratio (%)			36.8		
Repair & maint. ratio (%)	75	100	65	110	90
Labor ($ hr^{-1})			28.58		
Utilization rate (%)	60	65	75	75	65

Machine rate calculation

$$\boldsymbol{Machine\ rate}\ (\$\ \boldsymbol{hr^{-1}}) = \boldsymbol{Total\ owning\ cost}\ (\$\ \boldsymbol{hr^{-1}}) + \boldsymbol{Total\ operating\ cost}\ (\$\ \boldsymbol{hr^{-1}}) + \boldsymbol{Labor\ cost}\ (\$\ \boldsymbol{hr^{-1}})$$

Total owning cost

- $$\boldsymbol{Depreciation}\ (\$\ \boldsymbol{hr^{-1}}) = \frac{(\boldsymbol{Perchase\ price}(\$) \times (\mathbf{1} - \frac{\boldsymbol{Salvage\ value}(\%)}{\mathbf{100}})}{\boldsymbol{Economic\ life}(\boldsymbol{year}) \times \frac{\boldsymbol{SMH}}{\boldsymbol{year}}}$$

- $\boldsymbol{Average\ value\ of\ yearly\ investment}\ (\$\ \boldsymbol{hr^{-1}}) =$

$$\frac{\left(\boldsymbol{Perchase\ price}\ (\$)\ \times \left(\mathbf{1}\ -\ \frac{\boldsymbol{Salvage\ value}\ (\%)}{\mathbf{100}}\right)\right) \times (\boldsymbol{Economic\ life}\ (\boldsymbol{year}) + \mathbf{1})}{\mathbf{2}\ \times \boldsymbol{Economic\ life}\ (\boldsymbol{year})}$$

$$+\left(\boldsymbol{Perchase\ price}\ (\$)\ \times \left(\mathbf{1}\ -\ \frac{\boldsymbol{Salvage\ value}\ (\%)}{\mathbf{100}}\right)\right)$$

- $\boldsymbol{Total\ owning\ cost}\ (\$\ \boldsymbol{hr^{-1}}) =\ \boldsymbol{Depreciation}\ (\$\ \boldsymbol{hr^{-1}})$

$$+\ \boldsymbol{Average\ value\ of\ yearly\ investment}\ (\$\ \boldsymbol{hr^{-1}})\ \times (\mathbf{1} + \frac{\boldsymbol{Interst}\ (\%)}{\mathbf{100}} + \frac{\boldsymbol{Insureance}\ \&\ \boldsymbol{taxes}\ (\%)}{\mathbf{100}})$$

Total operating cost

- $\boldsymbol{Fuel\ cost}\ (\$\ \boldsymbol{PMH^{-1}}) =$

$$\boldsymbol{Horse\ power}\ (\boldsymbol{hp})\ \times \boldsymbol{Fuel\ use\ rate}\ (\boldsymbol{gallon\ hp}\ ^{-\mathbf{1}}\ \boldsymbol{PMH^{-1}})\ \times \boldsymbol{Deisel\ price}\ (\$\ \boldsymbol{gallon^{-1}})$$

- $$\boldsymbol{Lubricant\ cost}\ (\$\ \boldsymbol{PMH^{-1}}) =\ \boldsymbol{Fuel\ cost}\ (\$\ \boldsymbol{PMH^{-1}})\ \times \frac{\boldsymbol{Lubricant\ ratio}\ (\%)}{\mathbf{100}}$$

- $\boldsymbol{Repair}\ \&\ \boldsymbol{maintenence\ cost}\ (\$\ \boldsymbol{PMH^{-1}}) =$

$$\frac{\boldsymbol{Depreciation}\ (\$\ \boldsymbol{hr^{-1}}) \times \frac{\boldsymbol{R\&M\ ratio}\ (\%)}{\mathbf{100}}}{\frac{\boldsymbol{Utilization\ rate}\ (\%)}{\mathbf{100}}}$$

- $\boldsymbol{Total\ operating\ cost}\ (\$\ \boldsymbol{hr^{-1}}) =$

$$(\boldsymbol{Fuel\ cost}\ (\$\ \boldsymbol{PMH^{-1}}) + \boldsymbol{Lubricant\ cost}\ (\$\ \boldsymbol{PMH^{-1}}) + \boldsymbol{Repair}\ \&\ \boldsymbol{maintenence\ cost}\ (\$\ \boldsymbol{PMH^{-1}})) \times \frac{\boldsymbol{Utilization\ rate}(\%)}{\boldsymbol{100}}$$

The bottleneck function and its productivity are critical during a “hot” operation because it determines the entire system productivity. Once the bottleneck function is identified, one should try to adjust the system configuration to improve the system balance and thus the entire system productivity, especially when different functions in the system show large differences in productivity. Examples of system reconfiguration include changing the number of machines to be employed in the same function, replacing machines with higher (or lower) capacity ones, or decoupling functions to reduce interferences between machines (i.e., move to “cold” operations).

In this study, a total of six observed and hypothetical alternative configurations of the harvesting system were established either by changing number of machines in one function or substituting a particular machine with another in the same function (Figure 5). The first system configuration represents the system we observed during the field study. The second configuration was obtained by subtracting one skidder from the original configuration while keeping all the other machines the same. The third and fourth configurations exclusively used either two processors or two delimbers, respectively, for the delimbing and processing function. The fifth and sixth configurations were the same as the third and fourth configurations, respectively, but both employed only one skidder instead of two.

Each system configuration was evaluated in terms of unit production costs under various beetle-killed stand conditions to determine the most cost-effective system configuration for given conditions.

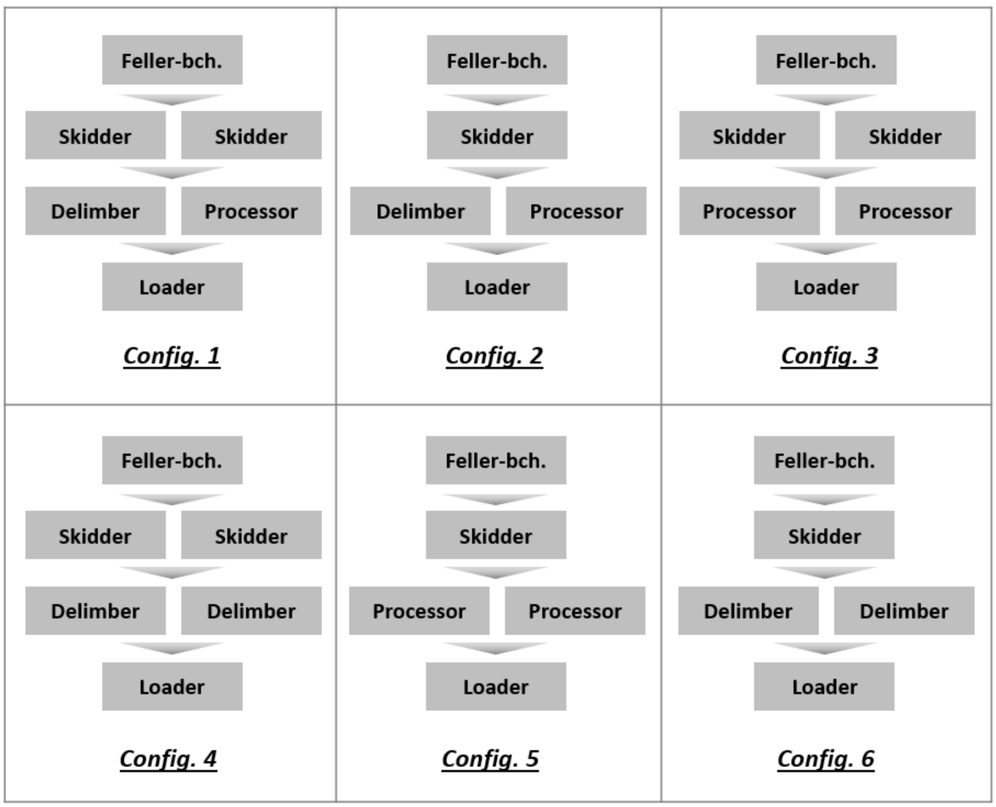

Figure 5. Six system configuration options analyzed in this study

3.4 Scenario Analysis for Different Stand Conditions

The scenario analysis was conducted to analyze the effects of different proportions of downed trees in beetle-killed stand harvesting. Five hypothetical stand conditions were developed with varying downed-tree proportions: 0%, 20%, 40%, 60%, and 80% of downed-trees in the stand (Table 6). The most cost-effective system configuration among the six alternatives (Figure 5) was determined based on the estimated unit costs of timber production.

We also analyzed the effect of a partially "cold" operation on system productivity where the feller-buncher was decoupled from the other machines in the system. We applied this "cold" operation concept to the system configurations where the feller-buncher became a bottleneck in order to examine the possibility of further improvement on the performance of the harvesting system.

Table 6. Harvesting scenarios with different proportions of downed-trees

Tree proportion	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Downed trees	**0%**	**20%**	**40%**	**60%**	**80%**
Standing trees	**100%**	**80%**	**60%**	**40%**	**20%**

4. Results

4.1 Data Examination for Linear Regression Model

The dataset of observed cycle times (Table 7) were utilized after removing the outliers in the dataset. Outliers were screened and removed after running the linear regression analysis between independent variables and cycle time, if they had more than 3 standard deviations from the mean. In total, 16 outliers, representing 1.6 percent of all observations, were removed from the dataset (five from feller-buncher, two from skidder, two from delimber, two from processor, and five from loader).

Table 7. Statistics of observed cycle times by machine

	Observed machine cycle time (sec cycle^{-1})			
	Collected data	Without outliers		
Machine	N	N	Mean	SE
Feller-buncher	282	277	28.85	11.55
Skidder	74	72	219.11	93.04
Delimber	231	229	36.36	10.66
Processor	227	225	25.39	8.98
Loader	207	202	27.49	10.08

For the feller-buncher, there was a statistically significant difference in cycle time between handling standing trees only and handling mixed trees with one or more downed trees (Welch t-test, p-value < 0.0001). The average cycle time was 7.2 seconds when the feller-buncher cut and bunched standing trees only, whereas it took 12.5 seconds (5.3 seconds more), on average, when the feller-buncher handled mixed trees with one or more downed trees (Figure 6).

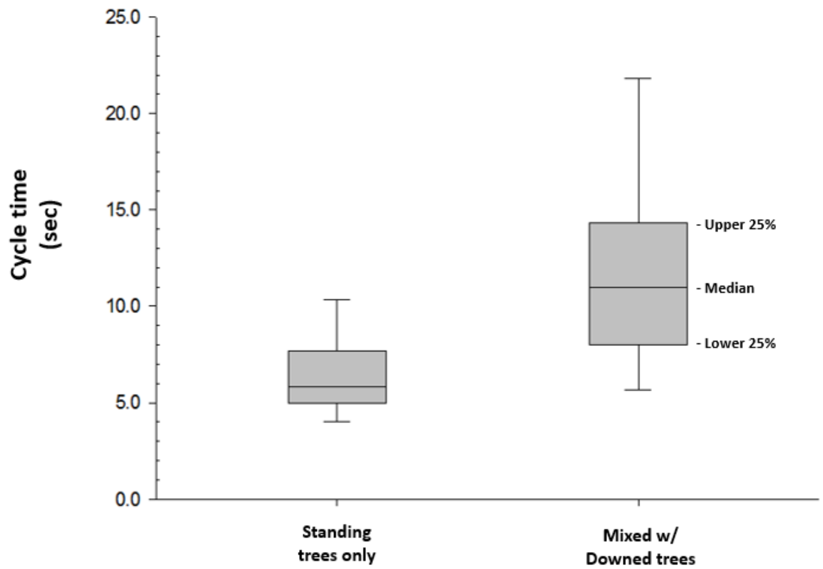

Figure 6. Box-plot graphs for feller-buncher cycle time in each tree group

Figure 7 presents the scatter plots for each of the independent variables (i.e., number of standing trees, number of downed trees, and travel distance) versus feller-buncher cycle time. There appears to be a general trend for cycle time to increase as the value of each independent variable increases, indicating that a correlation between feller-buncher cycle time and the independent variables. Spearman's rank-order correlation coefficients for cycle time and number of standing trees, number of downed trees, and travel distance, were 0.532, 0.264 and 0.542, respectively.

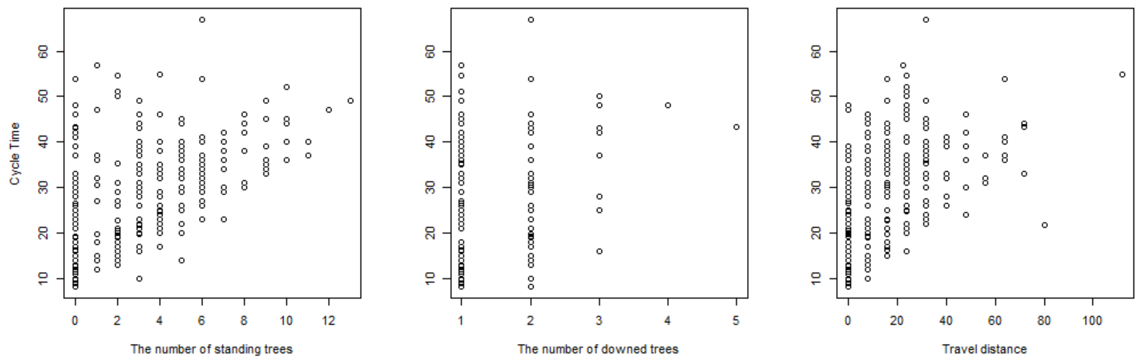

Figure 7. Scatter plots of independent variables and feller-buncher cycle time

Cycle times for the skidder seemed to be highly correlated with skidding distances in both machine movement directions, but moderately correlated with the number of pieces (Figure 8). Pearson's correlation coefficients for cycle time and empty distance, loaded distance, and number of trees, were 0.902, 0.913 and 0.117, respectively.

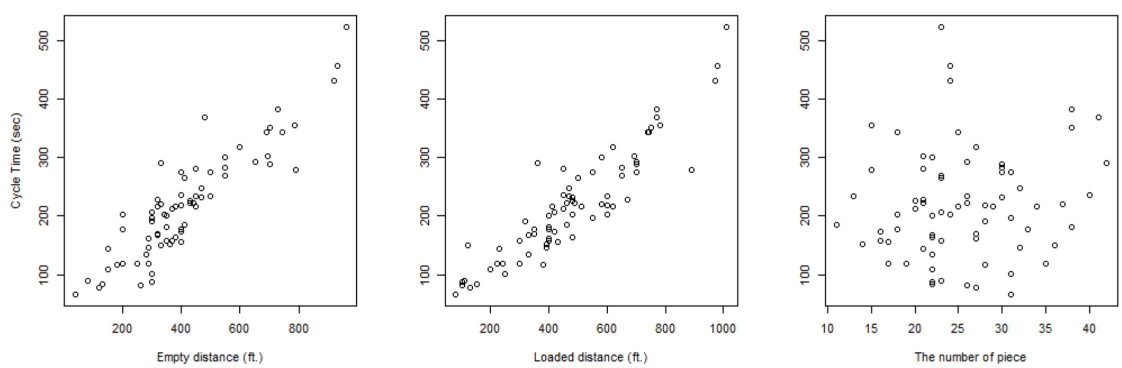

Figure 8. Scatter plots of independent variables and skidder cycle time

Cycle times of both the delimber and the processor appeared to respond somewhat differently depending on log grade. Cycle times of both processing machines had a relatively higher correlation with the number of sawlogs than the number of post and poles

(Figure 9). Overall correlation was weak. Spearman's rank-order correlation coefficients for delimber cycle time and number of sawlogs and number of post and pole, were 0.174 and 0.011, respectively, while correlations for processor cycle time for sawlog and post and pole were 0.255 and 0.092, respectively

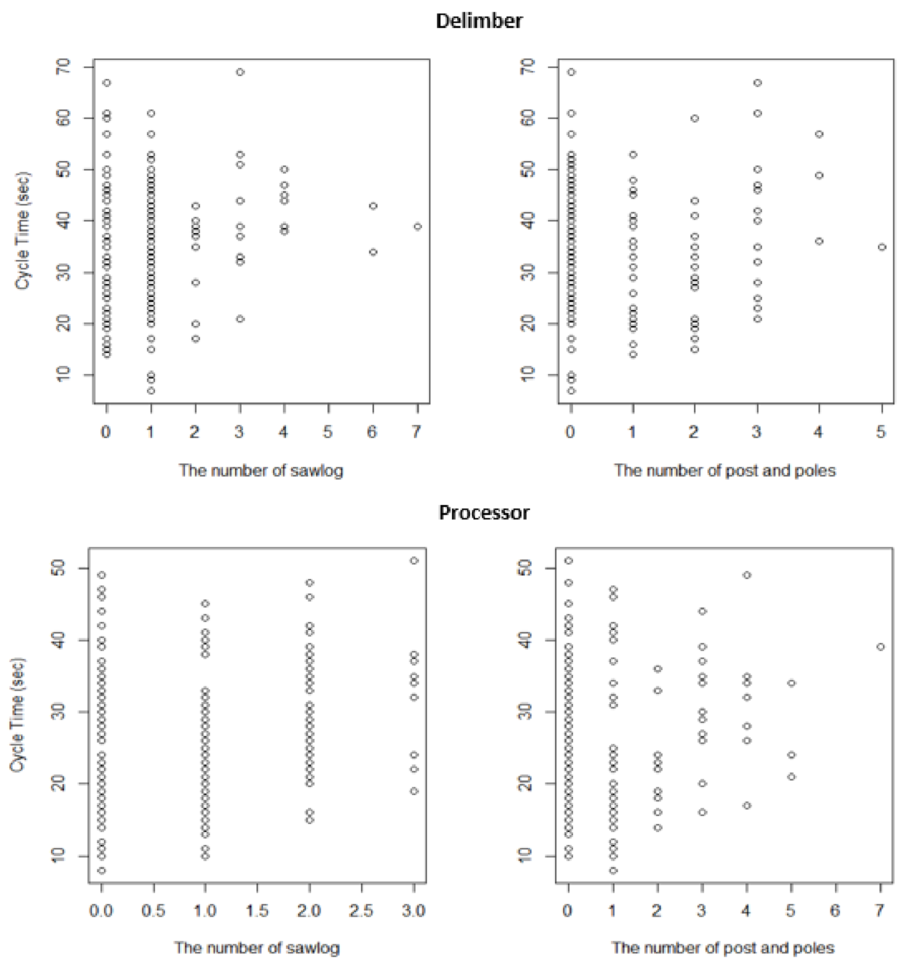

Figure 9. Scatter plots of independent variables and processing machine cycle times

The scatter plot for loader cycle time also showed that the cycle time is correlated with the number of logs the machine grabs during a cycle (Figure 10). The cycle time increased as the number of logs in a cycle increased. Spearman's rank-order correlation was 0.486.

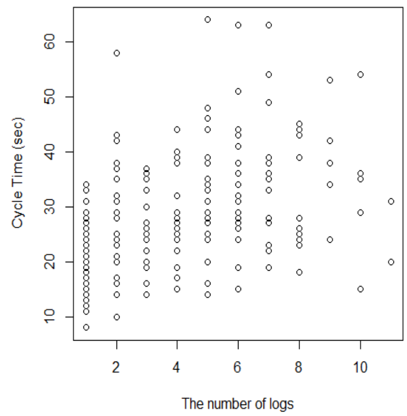

Figure 10. A scatter plot of the number of logs and loader cycle time

4.2 Delay Free Cycle Time Regression Models

Delay free cycle time regression models were developed for individual machines using the independent variables affecting machine cycle time (Table 8). The results indicated that the number of standing trees, the number of downed-trees, and travel distance were significant predictors for feller-buncher cycle time. It was estimated, on average, that one downed tree increased feller-buncher cycle time by 3.22 seconds compared to a standing tree, indicating that the downed tree was the most influential variable in the model (Table 8).

Three independent variables were included in the skidder cycle time model: empty travel distance, loaded travel distance, and the number of trees in a cycle (Table 8). One additional tree increased the cycle time by on average 2.339 seconds. Coefficients for empty travel distance and loaded travel distance were estimated as 0.218 and 0.225, respectively.

Two independent variables (i.e., number of sawlogs, number of post and poles) were included in the cycle time regression model for the delimber (Table 8). The number of sawlogs and the number of post and poles were estimated to have coefficients of 2.991 and 1.531, respectively. The delay free cycle time regression model for the loader included one explanatory variable, which was the number of logs with coefficient of 1.638 (Table 8).

Table 8. Delay free cycle time (sec) regression models by machine.

Machine	Parameter	Estimate	SE	t	P	Model P	Model adj. r^2
Feller buncher	Intercept	11.936	1.407	8.482	<0.0001	<0.0001	0.5406
	No. of standing trees	2.670	0.251	10.628	<0.0001		
	No. of downed trees	5.890	0.859	6.860	<0.0001		
	Travel distance	0.250	0.335	7.476	<0.0001		
Skidder	Intercept	-38.344	18.449	-2.078	0.0435	<0.0001	0.9189
	Distance (empty)	0.218	0.044	4.969	<0.0001		
	Distance (loaded)	0.225	0.041	5.512	<0.0001		
	No. of trees	2.339	0.655	3.571	0.0009		
Delimber	Intercept	31.388	1.588	19.771	<0.0001	0.008	0.0500
	No. of sawlogs	2.991	0.948	3.155	0.0019		
	No. of post and poles	1.531	1.012	1.512	0.1325		
Processor	Intercept	18.609	1.540	12.083	<0.0001	<0.0001	0.1337
	No. of sawlogs	4.820	1.009	4.778	<0.0001		
	No. of post and poles	2.807	0.681	4.120	<0.0001		
Loader	Intercept	20.424	1.300	15.719	<0.0001	<0.0001	0.2070
	No. of logs	1.638	0.273	5.998	<0.0001		

The variable ranges of the independent variables and their means are described by machine in Table 9 (the dependent variable, cycle time, is described in Table 7). The feller-buncher handled on average 4 trees in a cycle, including 3.3 standing trees and 0.7 downed trees. The mean of travel distance for the feller-buncher was 15.9 feet, and the mean cycle time of the feller-buncher was predicted to be 28.85 seconds when regression model is used to calculate the predicted mean cycle time from the means of independent variables.

The means of empty travel distance and loaded travel distance for the skidder were 418.8 ft. and 486.9 ft., respectively (Table 9). The loaded travel distance was longer than the empty travel distance because the skidder had to maneuver tree piles to a favorable position for the delimber or the processor at the landing location. On average, 24.2 trees were delivered by skidder in a cycle. Using the means of the independent variables in this regression model, the mean cycle time of the skidder was predicted to be 219.11 seconds.

On average, the delimber processed 0.9 sawlog and 0.6 post and poles per cycle, while the processor processed one sawlog and 0.7 post and poles per cycle (Table 9). Using the mean values of the independent variables in the regression models, the average cycle times of the delimber and the processor were predicted to be 35.1 seconds and 25.4 seconds, respectively. Average cycle time for the loader was predicted to be 26.8 seconds, after accounting for the mean of the independent variable which was 3.8 logs (Table 9).

The regression models have insignificant validation p-value provided by two-sample t-test between observed cycle time and predicted cycle time, indicating that there is no difference between the observed cycle time and predicted cycle time (Table 9). This indicates that the delay-free cycle time regression models can be used for predicting the cycle time of the harvesting machines that operate in the similar conditions as in the study site.

Table 9. Variable range and mean of independent variables, number of samples, and validated r^2 for each delay-free cycle time regression model

Machine	Independent variables	Variable range	Mean	N[1)]	Validated r^2 [2)]
Feller-buncher	No. of standing trees	0 to 13	3.3	185	0.472
	No. of downed trees	0 to 4	0.7		
	Travel distance	0 to 112	15.9		
Skidder	Distance (empty)	40 to 960	418.8	48	0.827
	Distance (loaded)	80 to 1010	486.9		
	No. of trees	14 to 41	24.2		
Delimber	No. of sawlogs	0 to 7	0.9	153	0.023
	No. of post and poles	0 to 4	0.6		
Processor	No. of sawlogs	0 to 3	1.0	150	0.214
	No. of post and poles	0 to 7	0.7		
Loader	No. of logs	1 to 11	3.8	135	0.154

1) Developed from randomly selected 67 percent of the data.

2) Developed from the reserved data (33 percent).

4.3 Productivity and Costs of Harvesting System

The average cycle time and turn size for individual machines are shown in Table 10. Even though the skidder had the largest average turn size of the machines used, it was not the most productive machine due to its long cycle time. Compared with other machines in the system, the productivities of the feller-buncher (40.60 t hr^{-1}) and loader (46.13 t hr^{-1}) were relatively high in the system mainly due to their fast cycle times. The delimber had the lowest productivity (15.88 t hr^{-1}) among machines because of its slow cycle time and small turn size. The processor had faster cycle times than the delimber with the similar turn size, resulting in higher productivity (23.93 t hr^{-1}).

The processor was the most expensive machine per scheduled machine hour (\$152.58 hr^{-1}), followed by the feller-buncher (\$141.35 hr^{-1}), and the skidder (\$122.58 hr^{-1}). The machine rates of the delimber and the loader were \$119.56 hr^{-1} and \$66.07 hr^{-1}, respectively (Table 10). The loader was the lowest cost machine among others mainly due to its low purchase price.

Table 10. Average cycle time, average turn size, productivity, and machine rate of each machine

Machine	Average cycle time[1)] (min. $cycle^{-1}$)	Average turn size (t $cycle^{-1}$)	Productivity (t hr^{-1} [2)])	Machine rate (\$ hr^{-1})
Feller-buncher	0.48	0.54	40.60	141.35
Skidder	3.65	3.28	35.03	122.58
Delimber	0.59	0.21	15.88	119.56
Processor	0.42	0.23	23.93	152.58
Loader	0.45	0.53	46.13	66.07

1) Delay-free cycle time in minutes.
2) Scheduled machine hour.

The productivity of the observed harvesting system was estimated at 39.81 t hr^{-1}, constrained by the processing function (Table 11). Trees at the landing were processed at the rate of 39.81 t hr^{-1} using a combination of two machines operating simultaneously: the delimber (15.88 t hr^{-1}) and the processor (23.93 t hr^{-1}). The skidding function, with two skidders operating simultaneously, had the highest productivity (70.06 t hr^{-1}) and was the most constrained function in the observed system.

The system cost of timber production is a function of unit costs of individual machines, as well as machine interactions causing system imbalance in terms of productivity. The unit cost of the system was estimated at \$18.21 t^{-1} (Table 11). The productivity of the processing function (39.81 t hr^{-1}) was slightly lower than the feller-buncher (40.60 t hr^{-1}), but the cost of processing (\$6.84 t^{-1}) was higher than the feller-buncher (\$3.55 t^{-1}). The processer and delimber together account for about 38 percent of the system cost, followed by the skidders at 34 percent (\$6.16 t^{-1}), and the feller-buncher, which accounted for 20 percent (\$3.55 t^{-1}) of the system cost.

Table 11. Productivity and unit costs of the observed harvesting system.

Machine		Productivity (t hr^{-1} [1]) One	Productivity (t hr^{-1} [1]) Combined	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher		40.60	40.60		3.55
Skidders (2)		35.03	70.06[2]		6.16[2]
Processing	Delimber	15.88	39.81[3]	39.81	6.84[3]
	Processor	23.93			
Loader		46.13	46.13		1.66
					18.21

1) Scheduled machine hour
2) Calculated for two skidders
3) Calculated for processing function

4.4 Optimal System Configurations

The six alternative system configurations were examined in terms of system productivity and unit cost of timber production (Table 12). System productivity ranged from 31.75 t hr^{-1} to 40.60 t hr^{-1} with Configuration 3 being the highest productivity, and Configurations 4 and 6 being the lowest. The unit cost of production ranged between \$17.19 t^{-1} and \$21.79 t^{-1}, and Configuration 2 was the lowest production cost system. The system used only one skidder while keeping all the other machines the same as the observed system (i.e., Configuration 1). In Configuration 2, the skidder became a bottleneck, limiting the entire system productivity, but one skidder provided a better balance in productivity among all machines. In contrast, the observed system with two skidders resulted in higher productivity of the skidding function that cannot be effectively balanced with other equipment, increasing non-productive time of the skidders and thus the system's cost of production.

Table 12. Unit cost of production of the six system configurations examined.

Configuration 1.

		Productivity (t hr^{-1}) One	Productivity (t hr^{-1}) Combined	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher		40.60	40.60	39.81	3.55
Skidder (2)		35.03	70.06		6.16
Processing	Delimber	15.88	39.81		6.84
	Processor	23.93			
Loader		46.13	46.13		1.66
					18.21

Configuration 2.

		Productivity (t hr^{-1}) One	Productivity (t hr^{-1}) Combined	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher		40.60	40.60	35.03	4.04
Skidder		35.03	35.03		3.50
Processing	Delimber	15.88	39.81		7.77
	Processor	23.93			
Loader		46.13	46.13		1.89
					17.19

Configuration 3.

		Productivity (t hr^{-1}) One	Productivity (t hr^{-1}) Combined	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher		40.60	40.60	40.60	3.48
Skidder (2)		35.03	70.06		6.04
Processing	Processor (2)	23.93	47.87		7.52
Loader		46.13	46.13		1.63
					18.67

Configuration 4.

		Productivity (t hr^{-1}) One	Productivity (t hr^{-1}) Combined	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher		40.60	40.60	31.75	4.45
Skidder (2)		35.03	70.06		7.72
Processing	Delimber (2)	15.88	31.75		7.53
Loader		46.13	46.13		2.08
					21.79

Configuration 5.

		Productivity (t hr^{-1}) One	Productivity (t hr^{-1}) Combined	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher		40.60	40.60	35.03	4.04
Skidder		35.03	35.03		3.50
Processing	Processor (2)	23.93	47.87		8.71
Loader		46.13	46.13		1.89
					18.13

Configuration 6.

		Productivity (t hr^{-1}) One	Productivity (t hr^{-1}) Combined	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher		40.60	40.60	31.75	4.45
Skidder		35.03	35.03		3.86
Processing	Delimber (2)	15.88	31.75		7.53
Loader		46.13	46.13		2.08
					17.93

4.5 Scenario Analysis on Downed-tree Proportions

The six system configurations were also examined for different site conditions of downed timber, ranging from 0% to 80% proportions of downed trees and the most-cost effective configuration was identified for each condition (Table 13).

Table 13. Changes in unit cost of the six system configurations with varying downed-tree proportions.

Downed-tree Proportion		**Config. 1**	**Config. 2**	**Config. 3**	**Config. 4**	**Config. 5**	**Config. 6**
0%	**Unit cost ($ t^{-1})**	**18.21**	**17.19**	**17.21**	**21.79**	**18.13**	**17.93**
	Bottleneck	**Proc.**	**Skid.**	**F-b**	**Proc.**	**Skid.**	**Proc.**
20%	**Unit cost ($ t^{-1})**	**18.21**	**17.19**	**18.67**	**21.79**	**18.13**	**17.93**
	Bottleneck	**Proc.**	**Skid.**	**F-b**	**Proc.**	**Skid.**	**Proc.**
40%	**Unit cost ($ t^{-1})**	**19.65**	**17.19**	**20.54**	**21.79**	**18.13**	**17.93**
	Bottleneck	**F-b**	**Skid.**	**F-b**	**Proc.**	**Skid.**	**Proc.**
60%	**Unit cost ($ t^{-1})**	**21.24**	**17.65**	**22.21**	**21.79**	**18.61**	**17.93**
	Bottleneck	**F-b**	**F-b**	**F-b**	**Proc.**	**F-b**	**Proc.**
80%	**Unit cost ($ t^{-1})**	**22.83**	**18.97**	**23.87**	**21.79**	**20.01**	**17.93**
	Bottleneck	**F-b**	**F-b**	**F-b**	**Proc.**	**F-b**	**F-b**

Configuration 2 was identified as the most cost-effective harvesting system configuration when the harvest unit had 0% - 60% downed trees. System unit cost did not change up to 40% downed trees because the skidder was the system bottleneck. However the system bottleneck started changing from skidder to feller-buncher at 60% downed trees. As a result, unit cost increased from \$17.19 t^{-1} to \$17.65 t^{-1}. As for 80% downed-tree proportion, Configuration 6 was identified as the least cost system (\$17.93 t^{-1}) with the feller-buncher being a system bottleneck.

The feller-buncher was the only machine affected by the presence of downed trees, and can be decoupled from skidders through implementing a “cold” operation. The benefit of the “cold” operation is that the feller-buncher works independently, with no interaction with the other machines in the system and therefore does not limit system productivity. In practice, this means the feller-buncher would move onto the unit and cut the stand well ahead of the skidder, creating enough buffer between the two functions. We examined this “cold” operation case for the 60% and 80% downed tree scenarios where the feller-buncher became a system bottleneck. As expected, the system unit cost in configuration 2 decreased by \$0.35 t^{-1}, for downed tree proportions of 60% (Table 14). Even though the system bottleneck was changed from feller-buncher to processing function, the system unit cost in configuration 6 did not change for downed tree proportions of 80% (Table 14).

Table 14. Unit costs of the cold operations on feller-buncher

	60% Downed-tree proportion stand Config 2.		80% Downed-tree proportion stand Config 6.	
	“Hot” operation	“Cold” operation on Feller-buncher	“Hot” operation	“Cold” operation on Feller-buncher
Unit cost (\$ t^{-1})	17.65	17.30	17.93	17.93
Bottleneck	Feller-buncher	Skidding	Feller-buncher	Processing

These results suggest that a harvesting system designed specifically for sites with large amounts of down timber can be a solution to a challenging harvest unit with beetle-killed trees, or trees downed by other disturbance events, such as severe wind. The results also illustrate the importance of harvest system reconfiguration in adapting to site conditions and reducing production costs compared the "one-size-fits-all" approach (Figure 11). As an example, had the observed system (i.e., Configuration 1) been used in 80% downed tree stands, the unit cost would increase by 25.4% compared to the unit costs for standing tree only stands, whereas the reconfigured harvesting system would increase the unit cost by only 4.3% when conditions change from 0% to 80% downed tree conditions.

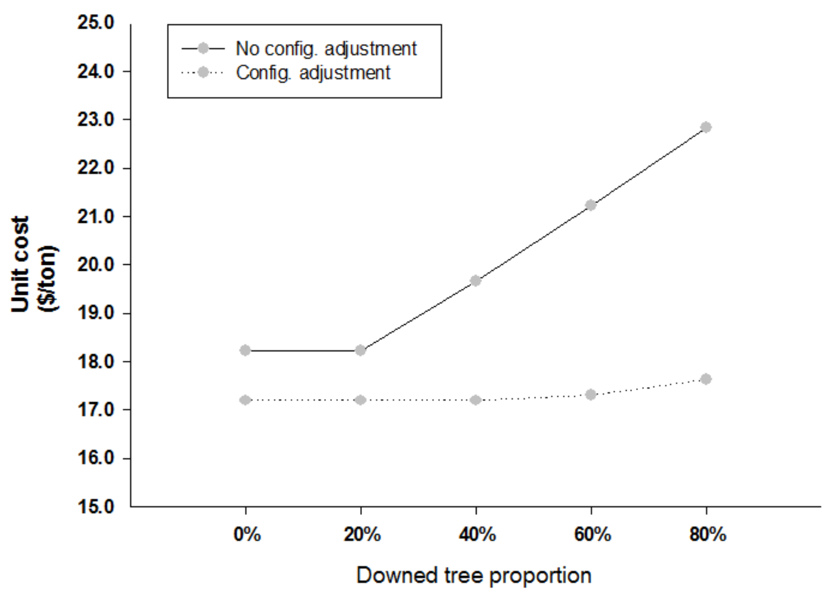

Figure 11. Unit costs before and after the configuration adjustment.

5. Discussion

5.1 The Effect of Downed-trees on the Feller-buncher Operation and Productivity

The major influence governing the productivity of the feller-buncher was the cycle time, which is highly affected by the number of downed trees in the stand. These results would be consistent with most practitioners' conventional wisdom because the machine would normally take more time to handle downed trees than standing trees due to extra movement of the feller-buncher head. This effect is especially severe in stands where fallen trees are almost horizontal. The feller-buncher used in this study can rotate its head 360 degrees from the horizontal axis and tilt up to 180 degrees from the vertical, allowing it to grasp downed trees on the ground without its disc saw contacting the ground soil. However, as observed, this action adds time and reduces productivity.

The cycle time differences between standing and downed trees likely to be closely connected to the characteristics of the machine head: maneuverability and saw-type. Feller-bunchers with less maneuverability in handling downed trees will increase the cycle time dramatically for handling downed or mixed trees. The continuous disk saw on the feller-buncher head was also presumably a factor, causing an increase of cycle time in handling downed trees. A feller-buncher with a continuous disk saw might be more efficient in cutting standing trees because it allows fast tree-cutting of multiple stems. However, the operator needs to be very cautious when handling downed trees avoid to hitting the ground with the disc saw. A feller-buncher with either a shear or bar saw might be slower in standing tree felling than a continuous disk saw. All these factors would affect the machine productivity under various tree conditions, as well as the cycle time difference between handling standing trees only and handling mixed trees for the same machine. These factors obviously have direct impacts on productivity and cost.

5.2 Productivity and Costs of Harvesting System and the Improvement

The unit production cost of \$18.21 t^{-1} from the observed harvesting system was within the production cost range reported in the previous studies. The unit cost can be converted into \$26.51 on a bone dry ton basis by assuming that the moisture contents of the trees were equivalent to the moisture contents (31.3%) of similar lodgepole pine trees studied by Luo et al. (2010). However, depending on the timing of mortality and weather, the moisture content of standing beetle-killed trees may be much lower. Even though it would be difficult to compare the system unit costs estimated from different sites, our unit cost was deemed comparable to the unit costs estimated from other timber harvesting productivity studies (Drews et al. 2001, Pan et al. 2007).

The productivity of the two skidders in the observed system was most restricted by the system bottleneck. Compared with the feller-buncher (40.60 t hr^{-1}) and the processing function (39.81 t hr^{-1}) in the system, the two skidders had high productivity (70.06 t hr^{-1}) that could not be matched by the other machines in the system. This imbalance of productivity among machines and functions reduced the overall system efficiency and thus increased harvesting costs. Reconfiguration of the harvesting system should be done in a way to alleviate the imbalance in productivity. When the skidder becomes a system bottleneck in Configuration 2, the skidding distance would be responsible for the production cost of the entire system as it is a highly influencing factor for skidder productivity. In such cases, the options to increase productivity can be explored to reduce skidding distances, such as adding log landings or employing more skidders. In the observed case, as noted previously, one of the skidder operators was new and training on the job, which may explain the contractor's choice to have two skidders running on a unit even though the skidding distance was relatively short.

5.3 Optimal Harvesting System Configurations

The proportion of downed trees in a stand affect the productivity of the feller-buncher. As feller-buncher productivity declines with increased downed trees, feller-buncher can become a bottleneck at a certain level of downed trees. The system productivity is then affected by downed-tree proportions. For instance, the unit costs of the observed system (i.e., Configuration 1) started to increase when the downed-trees proportion was around 40% when the feller-buncher becomes the bottleneck. Configuration 3 represents the case where feller-buncher was the system bottleneck regardless of downed tree proportions. As a result, the unit production cost of the system steadily increased as the downed-tree proportion increased. On the contrary, Configuration 4, for which productivity was limited by the processing function, showed no increase in production cost as the downed-tree proportion increased.

For most downed-tree proportions (0%, 20%, 40% and 60%), it turned out that Configuration 2 is the most cost-effective system configuration, alleviating the imbalances of machine productivity in the system. Whereas Configuration 2 was identified as the site-suitable harvesting system when the harvest unit has 0% - 60% downed trees, Configuration 6 started to become the optimal system configuration at a higher level of downed trees. This indicates that stand conditions including downed trees proportions are critical in determining the most cost-effective harvest system configuration.

In 60% downed-tree proportion stands, Configuration 2 was identified to the site-suitable system, compared to Configuration 6 (Table 15). Whereas the processing function (i.e., two delimbers) became the system bottleneck with the productivity of 31.76 t hr^{-1} in Configuration 6, feller-buncher had a productivity of 34.12 t hr^{-1} in Configuration 2, representing the most limiting function in the system in Configuration 2. Even though Configuration 6 had lower unit cost in the processing function (\$7.53 t^{-1}) than in Configuration 2 (\$7.98 t^{-1}), it was not enough to compensate for the unit costs difference in other functions (i.e., felling and bunching, skidding, and loading) between the two configurations, indicating that Configuration 2 had lower unit production cost (\$17.65 t^{-1}). This indicated that when the system bottleneck was changed from one to another function due to the reconfiguration, the unit costs for individual functions also change accordingly.

Table 15. Productivities and unit costs of Configurations 2 and 6 with 60% downed-tree proportion

	Configuration 2			Configuration 6		
Machine	Function productivity (t hr^{-1})	System productivity (t hr^{-1})	Unit cost ($ t^{-1})	Function productivity (t hr^{-1})	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher	34.12	34.12	4.14	34.12	31.76	4.45
Skidders	35.03		3.59	35.03		3.86
Processing	39.81		7.98	31.76		7.53
Loader	46.13		1.94	46.13		2.08
			17.65			17.93

In 80% downed-tree proportion stands, the feller-buncher was identified as the system bottleneck in both system Configurations 2 and 6 (Table 16). The difference in unit production costs was originated from the different unit cost of the processing function (i.e., \$8.57 t^{-1} from Configuration 2 and \$7.53 t^{-1} from Configuration 6). This difference in the processing function cost was due to the machine rate differences between the delimber and the processor. This indicated that if the bottleneck function remains the same before and after reconfiguration, the change of unit production cost is attributed by the cost difference between the machines employed for the bottleneck function.

Table 16. Productivities and unit costs of Configurations 2 and 6 with 80% downed-tree proportion

	Configuration 2			Configuration 6		
Machine	Function productivity (t hr^{-1})	System productivity (t hr^{-1})	Unit cost ($ t^{-1})	Function productivity (t hr^{-1})	System productivity (t hr^{-1})	Unit cost ($ t^{-1})
Feller-buncher	31.74	31.74	4.45	31.74	31.74	4.45
Skidders	35.03		3.86	35.03		3.86
Processing	39.81		8.57	31.76		7.53
Loader	46.13		2.08	46.13		2.08
			18.97			17.93

5.4 Harvesting the Beetle-killed Stands

Beetle infestations can result in large numbers of dead trees, and those trees are likely to fall on the forest floors over time. Mitchell et al. (1998) reported that 50% of trees in a beetle-killed lodgepole pine stand were down after 9 years and 90% were down after 14 years. They also reported that there was no significant difference in the fall rate by DBH of trees. Based on this study, it is reasonable to expect an increase in the harvesting costs in a beetle-impacted stand over time.

We assumed that the stands have the equivalent proportion of downed trees over time with the study of Mitchell et al. (1998). In the original configuration, the unit costs in stands of "9 years since death was estimated at \$20.44 t^{-1} and at \$23.63 t^{-1} in the stands of "14 years since death" (Table 17). With the optimal system configurations, the unit costs in a 9 years-since-death stand was estimated at \$17.19 t^{-1} with Configuration 2 and \$18.56 t^{-1} in a 14 years-since-death stand using Configuration 6, based on the predictive models.

Table 17. Downed-tree proportions on years since death and the estimated unit costs

	Years since death		
	5 years	**9 years**	**14 years**
Proportions[1)]			
- Downed-trees	**0%**	**50%**	**90%**
- Standing-trees	**100%**	**50%**	**10%**
Optimal system	**#2**	**#2**	**#6**
Based on the predictive model			
- Unit costs (observed system)	**\$18.21 t^{-1}**	**\$20.44 t^{-1}**	**\$23.63 t^{-1}**
- Unit costs (optimal system)	**\$17.19 t^{-1}**	**\$17.19 t^{-1}**	**\$18.56 t^{-1}**

1) Adapted from Mitchell et al. (1998)

Table 17 indicates that the unit costs of both observed and optimized systems tend to increase as the proportion of downed trees increases in the stand. If the increase of downed trees is a function of time passed after beetle infestation, this result implies that the longer the decision and implementation of salvage harvesting is postponed, the more expensive it would be to harvest beetle-killed stands. It is also suggested that optimally configured harvesting systems to respond to the conditions of beetle infested stands may be a solution to alleviate the cost increase caused by increased downed trees over time. Furthermore, there could be a significant loss in revenue due to the decline of timber product volume and value through breakage, decay, staining, checking and other scale and grade defects that intensify and accumulate over time.

The lumber recovery values as well as the harvesting unit costs are also important for utilizing the beetle-killed trees. Dobie et al. (1978) reported that positive conversion returns could be obtained from the lumber manufacturers, unless beetle-killed trees loose their bark and have severe checking on the surface. Lewis et al. (2006) also reported that the downed-trees were suitable for lumber production as the trees will fall to the ground before reaching the point where substantial decay occurs on their boles. This corresponds to the study results of Fraver et al. (2013), who stated that there is a lag period for unchanging log volume. The log volume will follow distinct depletion curves, once the initial lag period is over, due to decomposition (Fraver et al. 2013). The results indicate that the loss in lumber recovery is likely to be significant over time, recommending timely harvest decision of beetle-killed stands from the economic standpoint.

Stand regeneration and management of fuel loads are also important factors to be considered in harvesting beetle-killed stands. Salvage harvesting is important for regenerating lodgepole pines, regarded as a favorable timber species, in the beetle-infested stands, especially those managed for timber production objectives (Vyse et al. 2009). Collins et al. (2011) also reported that in lodegepole pine stands attacked by beetles, the subalpine fir will likely become the dominant species in un-harvested areas, whereas harvested areas maintain lodgepole pine as the most abundant species. With regard to fuel management, beetle-killed trees could substantially increase fuel loads in the forest, causing changes in fire behaviors, especially fire severity, and consequently increasing fire risks (Jenkins et al. 2008, Collins et al. 2012, Hicke et al. 2012).

In summary, well-timed harvesting in beetle-killed stands is advantageous in terms of harvesting costs and lumber recovery. Other values, such as the regeneration of favored species and fuel load management, would also increase the attractiveness and value of a timely harvesting decision. It is also recommended that the harvest system be site-specifically configured in order to minimize the cost of harvesting operations for given beetle-infested stand conditions.

6. Conclusion

Our study indicates that site conditions (standing vs. downed trees) not only affect the productivity of the feller-buncher, but can also affect the unit cost and productivity of the entire harvesting system because tree conditions can trigger the change of the system bottleneck in a combined felling, skidding and delimbing operation.

Our study suggests that the unit cost of timber production tends to increase as the proportion of downed trees increases in the stand, and quantifies this effect using detailed time study data. If the increase of downed trees is a function of time passed after beetle infestation, our results imply that the longer the decision is postponed on beetle-kill salvage harvest, the more expensive it would be to harvest beetle-killed stands.

Our study also suggests that site-specific, well-designed harvesting systems to respond to beetle-killed stand conditions may be a solution to reducing the cost increase attributed to increased downed trees in beetle-killed stands.

This study does not intend to provide accurate cost estimates of timber harvesting operations in beetle-killed stands because many other cost components were not considered in our cost models, such as fixed costs of landing and road building, site preparation costs, equipment move-in costs, profits and risks, etc. However, we hope that the machine cost and productivity prediction models developed in this study can provide forest managers and practitioners with useful insights about how downed-trees may change the cost structure of a harvesting system, as well as the optimal harvesting system configuration, allowing them to identify current barriers and opportunities for improvement. Timely harvesting decisions for beetle-infested stands may provide not only better economic benefits, but also help achieve other important stand and forest management objectives, such as stand regeneration and fuel management.

Bibliography

1. Adebayo, A.B., Han, H.-S. and Johnson, L. 2007 Productivity and cost of cut-to-length and whole-tree harvesting in a mixed-conifer stand. *For. Prod. J.*, **57** (6), 59.

2. Akhtari, S., Sowlati, T. and Day, K. 2014 Economic feasibility of utilizing forest biomass in district energy systems – A review. *Renewable and Sustainable Energy Reviews*, **33**, 117-127.

3. Anderson, N., Chung, W., Loeffler, D. and Jones, J.G. 2012 A productivity and cost comparison of two systems for producing biomass fuel from roadside forest treatment residues. *For. Prod. J.*, **62** (3), 222-233.

4. Baker, S.A., Westbrook, M.D. and Greene, W.D. 2010 Evaluation of integrated harvesting systems in pine stands of the southern United States. *biomass and bioenergy*, **34** (5), 720-727.

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

6. Brinker, R.W., Kinard, J., Rummer, R. and Lanford, B. 2002 Machine rates for selected forest harvesting machines.

7. Bureau of Labor Statistics. 2015 Occupational Employment Statistics: May 2015 State Occupational Employment and Wage Estimates. US Department of Labor, Washington. D.C.

8. Chow, S. and Obermajer, A. 2007 Moisture and blue stain distribution in mountain pine beetle infested lodgepole pine trees and industrial implications. *Wood Science and Technology*, **41** (1), 3-16.

9. Collins, B., Rhoades, C., Battaglia, M. and Hubbard, R. 2012 The effects of bark beetle outbreaks on forest development, fuel loads and potential fire behavior in salvage logged and untreated lodgepole pine forests. *Forest Ecology and Management*, **284**, 260-268.

10. Collins, B.J., Rhoades, C.C., Hubbard, R.M. and Battaglia, M.A. 2011 Tree regeneration and future stand development after bark beetle infestation and harvesting in Colorado lodgepole pine stands. *Forest Ecology and Management*, **261** (11), 2168-2175.

11. Corbett, L., Withey, P., Lantz, V. and Ochuodho, T. 2015 The economic impact of the mountain pine beetle infestation in British Columbia: provincial estimates from a CGE analysis. *Forestry*, cpv042.

12. Dobie, J. and Wright, D. 1978 Lumber values from beetle-killed lodgepole pine. *For. Prod. J.*

13. Dodson, E., Hayes, S., Meek, J. and Keyes, C.R. 2015 Montana logging machine rates. *International Journal of Forest Engineering*, **26** (2), 85-95.

14. Drews, E.S., Hartsough, B.R., Doyal, J.A. and Kellogg, L.D. 2001 Harvester-forwarder and harvester-yarder systems for fuel reduction treatments. *Journal of Forest Engineering*, **12** (1), 81-91.

15. Fraver, S., Milo, A.M., Bradford, J.B., D'Amato, A.W., Kenefic, L., Palik, B.J. *et al.* 2013 Woody debris volume depletion through decay: implications for biomass and carbon accounting. *Ecosystems*, **16** (7), 1262-1272.

16. Gara, R., Littke, W., Agee, J., Geiszler, D., Stuart, J. and Driver, C. 1985 Influence of fires, fungi and mountain pine beetles on development of a lodgepole pine forest in south-central Oregon.

17. Ghaffariyan, M. and Brown, M. 2013 Selecting the efficient harvesting method using multiple-criteria analysis: A case study in south-west Western Australia. *Journal of Forest Science*, **59** (12), 479-486.

18. Gibson, K., Kegley, S. and Bentz, B. 2009 Mountain pine beetle. *The Bark Beetles, Fuels, and Fire Bibliography*, 41.

19. Han, H.S. 2004 Economic feasibility of an integrated harvesting system for small-diameter trees in southwest Idaho. *For. Prod. J.*, **54** (2), 21-27.

20. Hicke, J.A., Johnson, M.C., Hayes, J.L. and Preisler, H.K. 2012 Effects of bark beetle-caused tree mortality on wildfire. *Forest Ecology and Management*, **271**, 81-90.

21. Howard, A.F. 1989 A sequential approach to sampling design for time studies of cable yarding operations. *Canadian Journal of Forest Research*, **19** (8), 973-980.

22. Hu, T., Johal, S., Yuen, B., Williams, T., Osmond, D. and Watson, P. 2006 Thermomechanical pulping and bleaching of blue-stained chips. *Pulp Pap. Can*, **107** (9), 38-45.

23. Jenkins, M.J., Hebertson, E., Page, W. and Jorgensen, C.A. 2008 Bark beetles, fuels, fires and implications for forest management in the Intermountain West. *Forest Ecology and Management*, **254** (1), 16-34.

24. Jiroušek, R., Klvač, R. and Skoupý, A. 2007 Productivity and costs of the mechanized cut-to-length wood harvesting system in clear-felling operations. *Journal of Forest Science*, **53** (10), 476-482.

25. Johansson, J. and Gullberg, T. 2002 Multiple tree handling in the selective felling and bunching of small trees in dense stands. *International Journal of Forest Engineering*, **13** (2), 25-34.

26. Kärhä, K., Rönkkö, E. and Gumse, S.-I. 2004 Productivity and cutting costs of thinning harvesters. *International Journal of Forest Engineering*, **15** (2), 43-56.

27. Kellogg, L., P. Bettinger, S. Robe, and A. Steffert. 1992 Mechanized harvesting: A compendium of research. *Forest Research Laboratory*, 401 p.

28. Kellogg, L.D. and Spong, B. 2004 Production and costs of cut-to-length thinning: experience from the Willamette Young Stand Project. Corvallis, Or.: Oregon State University, Forest Research Laboratory.

29. Kirk, P., Byers, J., Parker, R. and Sullman, M. 1997 Mechanisation developments within the New Zealand forest industry: the human factors. *Journal of Forest Engineering*, **8** (1), 75-80.

30. Kluender, R., Lortz, D., McCoy, W., Stokes, B. and Klepac, J. 1997 Productivity of rubber-tired skidders in southern pine forests. *For. Prod. J.*, **47** (11-12), 53-58.

31. Kumar, A. 2009 A conceptual comparison of bioenergy options for using mountain pine beetle infested wood in Western Canada. *Bioresource Technology*, **100** (1), 387-399.

32. Kumar, A., Flynn, P. and Sokhansanj, S. 2008 Biopower generation from mountain pine infested wood in Canada: An economical opportunity for greenhouse gas mitigation. *Renewable Energy*, **33** (6), 1354-1363.

33. Lanford, B. and Stokes, B.J. 1996 Comparison of two thinning systems. Part 2. Productivity and costs.

34. Légère, G. and Gingras, J.-F. 1998 *Evaluation of methods of harvesting with protection of small merchantable stems*. Forest Engineering Research Institute of Canada.

35. Lewis, K. and Thompson, D. 2006 Wood decay and degradation in standing lodgepole pine killed by mountain pine beetle. *Natural Resources Canada*.

36. Li, Y.X., Wang, J.X., Miller, G. and McNeel, J. 2006 Production economics of harvesting small-diameter hardwood stands in central Appalachia. *For. Prod. J.*, **56** (3), 81-86.

37. Lund, H.G. and Thomas, C.E. 1989 A primer on stand and forest inventory designs.

38. Luo, X., Gleisner, R., Tian, S., Negron, J., Zhu, W., Horn, E. *et al.* 2010 Evaluation of Mountain Beetle-Infested Lodgepole Pine for Cellulosic Ethanol Production by Sulfite Pretreatment to Overcome Recalcitrance of Lignocellulose. *Industrial & Engineering Chemistry Research*, **49** (17), 8258-8266.

39. Mitchell, R.G. and Preisler, H.K. 1998 Fall rate of lodgepole pine killed by the mountain pine beetle in central Oregon. *Western Journal of Applied Forestry*, **13** (1), 23-26.

40. Miyata, E.S. 1980 Determining fixed and operating costs of logging equipment.

41. Nakagawa, M., Hamatsu, J., Saitou, T. and Ishida, H. 2007 Effect of tree size on productivity and time required for work elements in selective thinning by a harvester. *International Journal of Forest Engineering*, **18** (2), 24-28.

42. Nurminen, T., Korpunen, H. and Uusitalo, J. 2006 Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fennica*, **40** (2), 335-363.

43. Olsen, E.D. and Kellogg, L.D. 1983 Comparison of time-study techniques for evaluating logging production. *Transactions of the ASAE*, **26** (6), 1665-1668.

44. Orbay, L. and Goudie, D. 2006 Quantifying lumber value recovery from beetle-killed trees.

45. Ovaskainen, H., Uusitalo, J. and Väätäinen, K. 2004 Characteristics and significance of a harvester operators' working technique in thinnings. *International Journal of Forest Engineering*, **15** (2), 67-77.

46. Pan, F., Han, H.-S., Johnson, L.R. and Elliot, W.J. 2007 Production and cost of harvesting, processing, and transporting small-diameter (≤ 5 inches) trees for energy. *Forest* (10380).

47. Pan, X., Xie, D., Yu, R.W. and Saddler, J.N. 2008 The bioconversion of mountain pine beetle-killed lodgepole pine to fuel ethanol using the organosolv process. *Biotechnology and Bioengineering*, **101** (1), 39-48.

48. Purfürst, F.T. and Erler, J. 2011 The human influence on productivity in harvester operations. *International Journal of Forest Engineering*, **22** (2), 15-22.

49. Richardson, R. and Makkonen, I. 1994 *The performance of cut-to-length systems in eastern Canada*. Forest Engineering Research Institute of Canada.

50. Robinson, R.C. 1962 Blue stain fungi in lodgepole pine (Pinus contorta Dougl. var. latifolia Engelm.) infested by the Mountain Pine Beetle (Dendroctonus monticolae Hopk.). *Canadian Journal of Botany*, **40** (4), 609-614.

51. Shore, T.L., Safranyik, L., Hawkes, B.C. and Taylor, S.W. 2006 Effects of the mountain pine beetle on lodgepole pine stand structure and dynamics. *The mountain pine beetle: A synthesis of biology, management, and impacts on lodgepole pine. L. Safranyik and B. Wilson (editors). Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, Victoria, BC*, 95-116.

52. Telsang, M. 2006 *Industrial engineering and production management*. S. Chand.

53. U.S. Energy Information Administration. 2016 Petroleum & other liquids: gasoline and diesel fuel update. U.S. Department of Energy, Washington. D.C.

54. USDA Forest Service. 2015 Forest Insect and Disease Conditions, Rocky Mountain Region. *USDA Forest Service. State & Private Forestry & Tribal Relations*, p. 119pp.

55. Vyse, A., Ferguson, C., Huggard, D.J., Roach, J. and Zimonick, B. 2009 Regeneration beneath lodgepole pine dominated stands attacked or threatened by the mountain pine beetle in the south central Interior, British Columbia. *Forest Ecology and Management*, **258**, S36-S43.

56. Wang, J.X., Long, C. and McNeel, J. 2004 Production and cost analysis of a feller-buncher and grapple skidder in central Appalachian hardwood forests. *For. Prod. J.*, **54** (12), 159-167.

57. Woudenberg, S.W., Conkling, B.L., O'Connell, B.M., LaPoint, E.B., Turner, J.A. and Waddell, K.L. 2010 The Forest Inventory and Analysis Database: Database description and users manual version 4.0 for Phase 2.

58. Zacher, A.H., Elliott, D.C., Olarte, M.V., Santosa, D.M., Preto, F. and Iisa, K. 2014 Pyrolysis of woody residue feedstocks: upgrading of bio-oils from

mountain-pine-beetle-killed trees and hog fuel. *Energy & Fuels*, **28** (12), 7510-7516.