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harvesting & operations

Effect of Downed Trees on Harvesting Productivity and Costs in Beetle-Killed Stands

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The mountain pine beetle (*Dendroctonus ponderosae*) has affected millions of acres of forests in the Rocky Mountain region in the United States. This study quantified the difficulty of harvesting beetle-killed stands caused by downed trees. A detailed time study was conducted on a whole-tree clearcut harvest using a ground-based system in western Montana in August 2015. Our study shows that the productivity of the feller-buncher was highly affected by the number of downed trees. The feller-buncher average cycle time per tree was 7.0 s when only standing trees were cut and bunched whereas it took 13.2 s per tree when the bunch included one or more downed trees. Our results also indicate that stand conditions with various levels of downed trees affect the unit production cost and productivity of the entire harvesting system by increasing operational delays in the combined felling, skidding, and delimbing operation. This research provides insight into how optimized system configurations may help cope with the increase in harvesting cost caused by beetle-killed stand conditions and helps quantify the potential financial impacts of delayed stand management decisions in the wake of high-mortality forest disturbances.

Keywords: time study, forest equipment, system balance, mountain pine beetles, salvage harvest

The recent outbreak of the mountain pine beetle (*Dendroctonus ponderosae*) has affected a large area of forests in North America, leaving extensive tree mortality in almost 45 million acres in British Columbia, Canada and 10 million acres in the Rocky Mountain region of the United States (Corbett et al. 2015, 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 (*Pinus contorta*) trees and kill the live trees by interrupting nutrient and water transport (Gibson et al. 2009). After the tree is dead, it loses its firmness because of bole decay and eventually falls to the forest floor, changing the stand structure (Mitchell and Preisler 1998).

Depending on site conditions and ownership objectives, it may be beneficial to harvest dead trees for economic value recovery, stand regeneration, and fire risk mitigation (Collins et al. 2011, 2012; Hicke et al. 2012; Hu et al. 2006; Orbay and Goudie 2006). Such treatments implemented primarily to recover economic value are known as salvage harvests, whereas treatments to alter fire behavior and spread are commonly called fuel treatments and often include prescribed burning in addition to cutting both live and dead trees. In light of the widespread mortality caused by the mountain pine beetle, and given the increasing recognition of the social and environmental benefits of biomass energy and bio-based products, beetle-killed wood and harvest residues have been recently studied as a feedstock source for bioenergy products (Akhtari et al. 2014, Kumar et al. 2008, Zacher et al. 2014). However, despite the potential positive impacts of the salvage harvest, there exist many uncertainties related to beetle-killed stand harvesting in terms of safety, costs, and recoverable products and their values. There is also some concern that clearcut salvage harvests in particular may have negative effects on soils and advance regeneration in these stands, depending on site conditions.

From economic, environmental, and safety perspectives, thoughtful harvesting system design is essential for successful harvesting operations in any forest. Various factors related to stand characteristics, sensitive resources, terrain conditions, and road infrastructure should be taken into account in harvest unit layout and system design to protect the site, maintain high productivity, and reduce production costs (Kellogg and Spong 2004).

There have been many studies concerning the performance of different harvesting systems under various difficult stand and terrain conditions. For example, Wang et al. (2004) investigated the production and cost of harvesting operations using a tracked

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Figure 1. A typical stand of lodgepole pine with high beetle mortality showing a mix of standing live, standing dead, leaning dead, and down dead trees.

feller-buncher and a rubber-tired grapple skidder applied to four hardwood sites in north-central Appalachia. Bolding et al. (2009) assessed the productivity and cost of the similar equipment applied to fuel reduction operations in a mixed conifer stand in southwest Oregon. Both studies examined the ground-based harvesting system that is also common in the Rocky Mountain region, and the fuel reduction operations in Bolding et al. (2009) were similar in some ways to beetle-killed stand harvesting in that the harvest of small, nonmerchantable trees is often integrated into commercial harvesting operations. However, the stand conditions in beetle-killed stands with many downed trees are different from those studied in the past, and there is no previous study that has specifically looked at beetle-killed stand harvesting operations with the existence of a wide range of downed tree conditions.

The unique characteristics of beetle-killed forest stands with widespread downed trees can affect the productivity and costs of harvesting equipment and the system as a whole (Figure 1). This study attempted to address the effects of the existence of downed trees in beetle-killed stands on harvesting costs and productivity. We conducted a detailed time study on harvesting of beetle-killed lodgepole pine in western Montana on a stand that was clearcut using a ground-based whole-tree mechanized harvesting system. The study was designed not only to develop a new cost prediction model for beetle-killed stand harvesting but also to provide useful insights about how different proportions of downed trees may change the optimal harvesting system configuration, allowing forest managers and practitioners to identify and overcome current barriers and improve opportunities and outcomes under these difficult conditions.

The specific objectives of this study include quantifying the effects of downed trees on the performance of feller-buncher equipment, developing predictive cost and productivity models for a whole-tree mechanized harvesting system applied to beetle-killed stands with various downed tree proportions, and demonstrating the utility of the predictive models in configuring the most cost-effective harvesting system under given stand conditions.

Methods

Study Site and Harvesting System

The study harvest unit is a 27-ac mixed-conifer stand located on a gentle slope northwest of Chessman Reservoir (46° 28′ N, 112° 11′ W) in western Montana (Figure 2). The dominant tree species was lodgepole pine (*P. contorta*), and the stand was attacked by mountain pine beetles in 2008. Preharvest stand inventory data were collected using Lund's methods (Lund and Thomas 1989) to provide unbiased sampling plot locations throughout the harvesting unit (Table 1). A total of 21 fixed-area sample plots of 0.08-ac size were established with 5% sampling intensity using a grid of equilateral triangles on the harvesting unit.

A whole-tree clearcut with a ground-based mechanized harvesting system was applied to the unit with six pieces of equipment: one tracked feller-buncher (Tigercat LX830C with 5702 felling saw), two rubber-tired grapple skidders (John Deere 848H and Caterpillar 535C), one dangle-head processor (Link-Belt 290 with a Waratah 623-head), one stroke boom delimber (Link-Belt 2800 with a Denharco-head), and one log loader (John Deere 690E LC). All of the equipment was operated on the site simultaneously, with logs loaded and transported from the site during the harvest operations (i.e., a "hot" operation). All of the machine operators were experienced except for the Caterpillar 535C skidder operator, who was new and training on the job.

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 recorded for individual machine operations during the field study. Independent variables hypothesized to affect cycle time were recorded along with each cycle time of the machine (Table 2). Distance of machine movement was measured using a laser rangefinder, and the number of trees per cycle was visually counted.

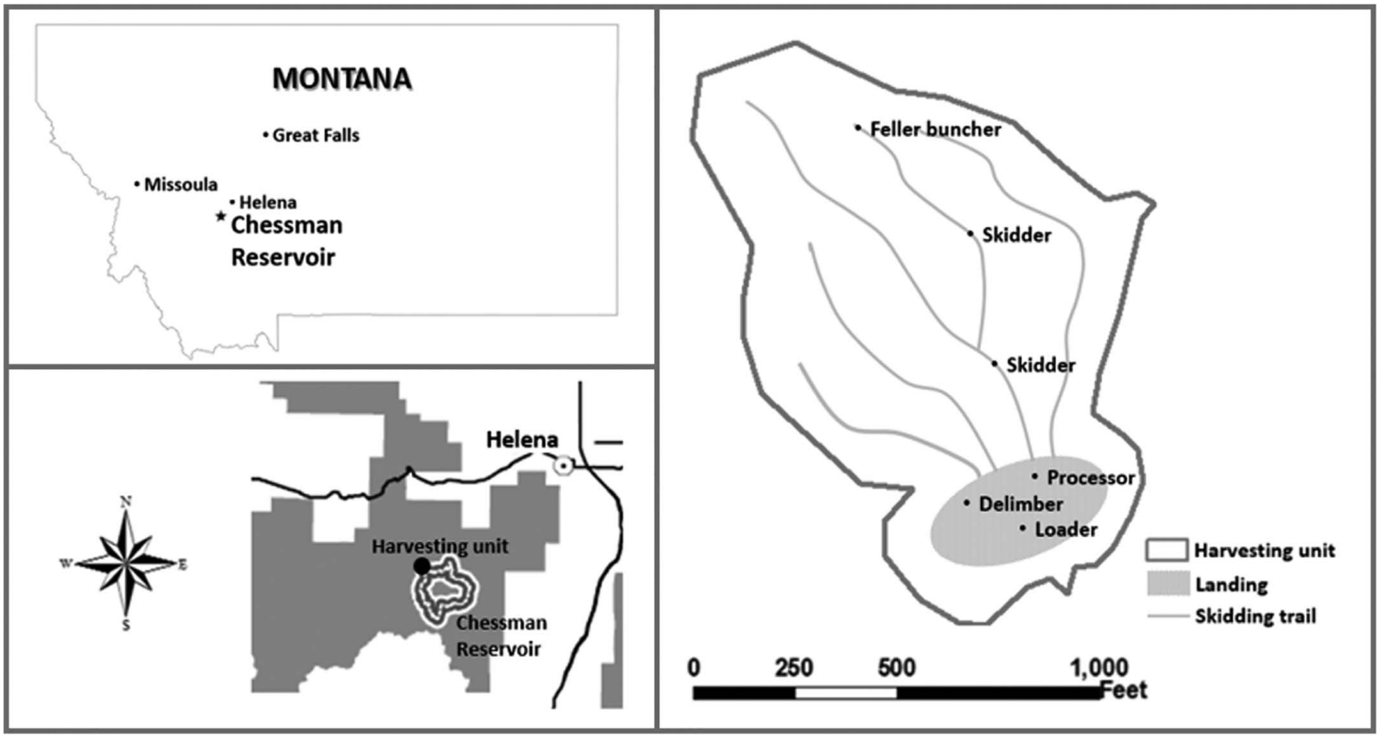

Figure 2. Site map showing the harvesting unit with general locations of equipment in the unit: the feller-buncher working the edge of the cut, the skidders transporting whole trees to the landing, the processor and delimber processing the trees, and the loader pilling and loading the processed logs onto a truck.

Table 1. Characteristics of the study harvesting unit.

Characteristic	Value
Total area	27 ac
Average ground slope	9%
Quadratic mean diameter	7.5 in.
Average tree height	42.9 ft
Basal area per acre	202.1 ft^2 ac^{-1}
Stand density	655 trees ac^{-1}
Year of infestation	2008
Species proportion	
Lodgepole pine	91.0%
Douglas-fir	8.8%
Subalpine fir	0.2%
Tree condition proportion	
Standing trees	78.0%
Downed trees	22.0%

Table 2. Time elements for each machine cycle and associated predictor variables.

Equipment	Time element per cycle	Predictor variables
Feller-buncher	1. Moving to trees	Travel distance (ft)
	2. Positioning the felling head and felling	Number of standing trees*
	3. Bunching	Number of downed trees*
Skidder	1. Traveling empty	Empty travel distance (ft)
	2. Positioning and grappling	Number of trees*
	3. Traveling loaded	Loaded travel distance (ft)
	4. Unloading	
Delimber and processor	1. Grappling	Number of sawlogs*
	2. Delimbing, processing, and sorting	Number of post and pole logs*
Loader	1. Grappling	Number of logs*
	2. Loading	

* These variables were also used for production measurement.

We classified various tree conditions into two categories: standing and downed. Standing trees were those with an unbroken portion of the bole at least 4.5 ft in length from the ground, leaning less than 45° from vertical (Woudenberg et al. 2010). Downed trees were those that had an unbroken bole of at least 4.5 ft but were partially or completely detached from the stump leaning more than 45° from vertical. Trees that were completely downed with full contact with the ground were also counted as downed trees.

Data collected 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. The primary justification for this is that the models predict delay-free cycle time, and occasionally there is some incident with the operator, such as a brief radio call, that cannot be clearly identified as a delay by the observer but can have a significant impact on the cycle time for machines. We evaluated data using correlation statistics (i.e., Pearson's correlation and Spearman's rank-order correlation). Pearson's correlation was used to measure the linear correlation between independent and dependent variables with assumptions of normality, linearity, and constant variance. Spearman's rank-order correlation was used for the monotonic correlation when the assumptions of the Pearson's correlation were not satisfied.

We randomly selected 67% of the data for model training and used the rest of the data for model validation (Pan et al. 2008). In this approach, *R* values between predicted and observed cycle times were computed to measure how close the observed data (i.e., validation data) were to the estimates generated using the regression model developed with the training data (Adebayo et al. 2007).

The feller-buncher often cuts and bunches multiple trees in a cycle. To analyze the effects of downed trees in a tree bunch, we classified the cycle times into two groups, with one group including

Table 3. Cost parameters used in machine rate calculations.

	Feller-buncher	Skidder	Delimber	Processor	Loader
Equipment Model	Tigercat LX830C	JD 848H	Link-belt 2800 Denharco head	Link-belt 290 Waratah head	JD 690E LC
Purchase price ($)	500,000	369,444	442,853	513,971	176,666
Horsepower (hp)	300	200	194	177	140
Salvage value (%)	15	15	20	20	30
Economic life (years)	5	5	5	5	5
SMH yr^{-1}*	2,000	2,000	2,000	2,000	2,000
Interest rate (%)	10.0	10.0	10.0	10.0	10.0
Insurance and taxes (%)	3.5	5.0	2.0	4.0	1.5
Diesel price ($·$gal^{-1}$)	2.50	2.50	2.50	2.50	2.50
Fuel use rate (gal·hp^{-1}·PMH^{-1})*	0.0263	0.0292	0.0292	0.0292	0.0217
Lubrication†	36.8	36.8	36.8	36.8	36.8
Repair and maintenance‡	75	100	65	110	90
Labor ($·$SMH^{-1}$)§	28.58	28.58	28.58	28.58	28.58
Utilization rate (%)	60	65	75	75	65

* Scheduled machine hour (SMH) and productive machine hour (PMH).
† Lubrication is a percentage of fuel cost.
‡ Repair and maintenance is a percentage of straight-line depreciation.
§ Labor includes both wage and fringe benefits.

only standing trees and the second group including one or more downed trees. We then compared the two groups using the Welch *t* test and analyzed the difference in average cycle time.

Harvesting System Productivity and Production Cost

The hourly productivities of individual machines were estimated using the production data observed during the field study and the estimated average delay-free cycle time obtained from the regression models. Because of the relatively small diameter and short height of trees in this stand (Table 1), most of the harvested trees yielded only one 36-ft log per tree with a minimum small-end diameter of 4 in. We estimated each turn size using the number of logs per turn and the average log weight in US short ton (ton). The average log weight was estimated based on the average number of logs loaded on a truck and the average net weight of truck loads obtained from corresponding mill trip tickets.

For machine utilization rates, we applied the commonly used rates published in Brinker et al. (2002) to estimate generalized machine productivities while accounting for unknown or irregular delay times (Brinker et al. 2002, Dodson et al. 2015, Kellogg et al. 1992). Machine hourly rates of individual machines were calculated using the standard machine rate calculation method (Miyata 1980). Table 3 shows the data and information used in machine rate calculations in this study.

Individual machine productivities and machine hourly rates were then combined together to estimate the productivity and unit production cost of the entire harvesting system. The limiting "bottleneck" machine (or function if more than one machine was conducting the same function at the same time, as in the case of the skidder) was identified as the one with the lowest productivity in the harvesting system, and its productivity was used to determine the productivity of the entire system. We assumed the system included two John Deere 848H skidders because the other skidder operator (Caterpillar 535C) was new and training on the job and was therefore deemed nonrepresentative. Unit production cost was estimated on a green mass basis in US dollars per US short ton ($ ton^{-1}).

It should be noted that this approach does not adequately provide an accurate estimate of total project costs because many other fixed and variable cost components are not considered in the cost models, such as the fixed costs of landing and road building, site preparation, equipment move in/move out, profits and risks, administration, and other considerations. Even so, this approach is extremely useful for comparing the production costs of alternative harvesting systems and understanding the effects of both site and system variables on the cost of production.

System Configuration and Scenario Analysis for Different Stand Conditions

The bottleneck function in the harvesting system and its productivity are critical during "hot" operations because the bottleneck determines the productivity of the entire system. Once the bottleneck function is identified, the system configuration may be adjusted to improve the system balance with different machines or practices or by increasing "buffers" between functions. Buffers are typically production offsets that help balance an otherwise unbalanced system. For example, the feller-buncher may begin work earlier than the skidders to stockpile tree bunches ahead of time. To test different system configurations, we developed five alternative configurations either by changing the number of machines in one function or by substituting a particular machine with another that accomplishes the same function. Configuration 1 in Figure 3 represents the system we observed during the field study. Configuration 2 uses only one skidder while keeping all of the other machines the same. Configurations 3 and 4 use either two processors or two delimbers, respectively, but not a combination of one processor and one delimber as we observed. Configurations 5 and 6 are similar to Configurations 3 and 4, respectively, but both use only one skidder instead of two.

Each system configuration was evaluated in terms of unit production costs under different beetle-killed stand condition scenarios. Five hypothetical scenarios were developed with varying downed tree proportions: 0, 20, 40, 60, and 80% of downed trees in the stand. The most cost-effective system configuration among the six alternatives was then determined based on the lowest estimated unit production cost.

We also analyzed the effect of a system in which the feller-buncher was decoupled from the other machines in the system. We applied this "decoupled" operation to the system configurations in

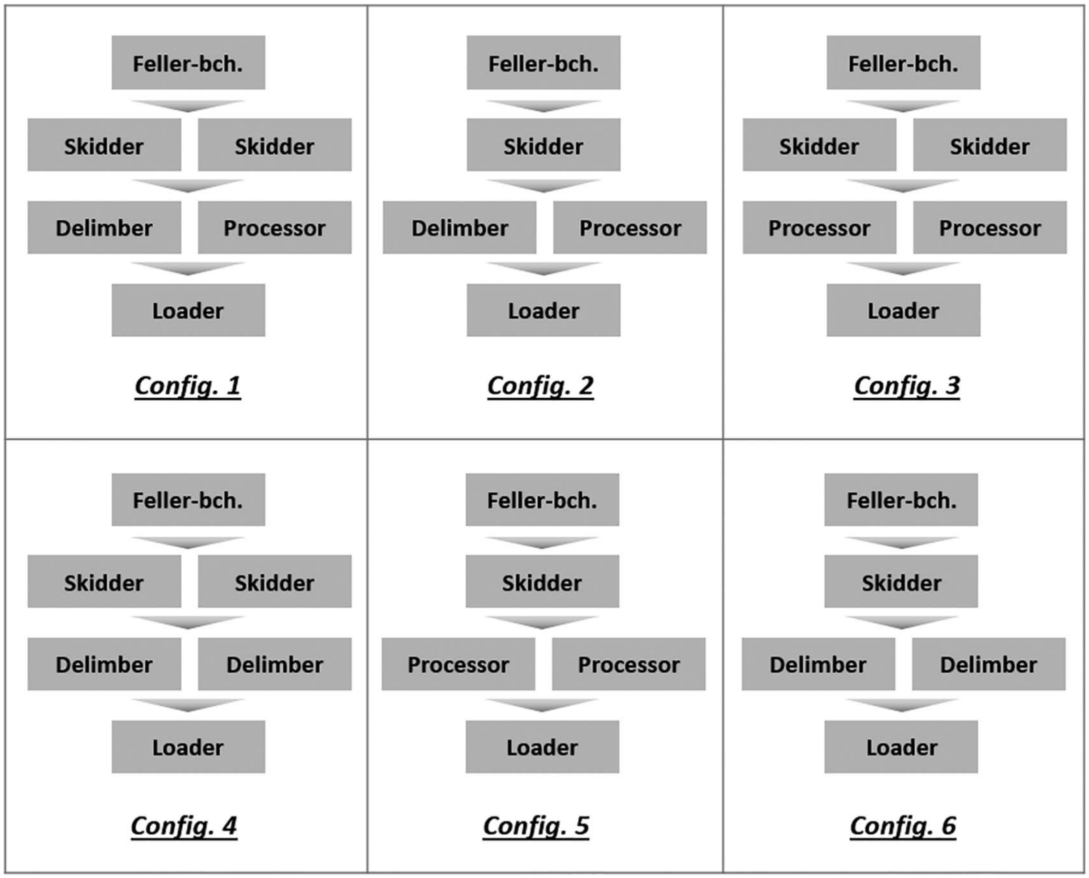

Figure 3. Six harvesting system configurations analyzed in this study.

Table 4. Statistics of observed cycle times by equipment.

Equipment	Observed machine cycle time (s cycle^{-1})			
	All observations	Without outliers		
	Number of cycle times	Number of cycle times	Mean	Standard error
Feller-buncher	282	277	28.73	11.55
Skidder	74	72	219.01	93.04
Delimber	231	229	35.14	10.66
Processor	227	225	25.82	8.98
Loader	207	202	26.60	10.08

which the feller-buncher was the bottleneck to examine the possibility of further improving the performance of the harvesting system.

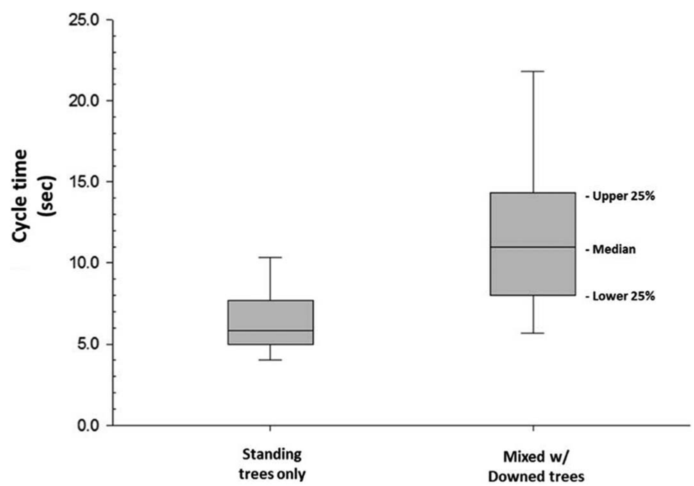

Figure 4. Box–plot graphs for feller-buncher cycle time on a per-tree basis in each tree group.

Results

Delay-Free Cycle Time Regression Models

The total number of cycle times collected during the field study ranged from 74 to 282 depending on the machine being observed (Table 4). After performing the linear regression analysis between cycle time and independent variables, a total of 16 outliers, representing 1.6% of all observations, were removed from the data set.

During feller-buncher operations, there was a statistically significant difference in cycle time between handling standing trees only and handling mixed trees with one or more downed trees in the bunch (Welch t test, $P < 0.0001$). The average cycle time per tree was 7.0 s when the feller-buncher only cut and bunched standing trees whereas it took 13.2 s, on average, when the feller-buncher handled mixed trees (Figure 4).

The scatterplots between individual machine cycle times and their explanatory variables, as well as Pearson's correlation coefficients (or Spearman's rank-order correlation if assumptions for Pearson's were not met), suggest that each machine cycle time is positively related to all of the explanatory variables with a different level of linear dependence ranging between 0.011 and 0.913. Among all of the pairs of dependent and independent variables analyzed, skidder cycle time and loaded travel distance showed the

Table 5. Parameters and statistics for delay-free cycle time (s) regression models by machine.

Machine	Parameter	Estimate	Standard error	*t*	*P*	Model *P*	Model adjusted R^2
Feller-buncher	Intercept	11.936	1.407	8.482	<0.0001	<0.0001	0.5406
	Number of standing trees	2.670	0.251	10.628	<0.0001		
	Number of downed trees	5.890	0.859	6.860	<0.0001		
	Travel distance (ft)	0.250	0.335	7.476	<0.0001		
Skidder	Intercept	−38.344	18.449	−2.078	0.0435	<0.0001	0.9189
	Distance empty (ft)	0.218	0.044	4.969	<0.0001		
	Distance loaded (ft)	0.225	0.041	5.512	<0.0001		
	Number of trees	2.339	0.655	3.571	0.0009		
Delimber	Intercept	31.388	1.588	19.771	<0.0001	0.008	0.0500
	Number of sawlogs	2.991	0.948	3.155	0.0019		
	Number 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
	Number of sawlogs	4.820	1.009	4.778	<0.0001		
	Number 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
	Number of logs	1.638	0.273	5.998	<0.0001		

Table 6. Variable ranges and means 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**	Validated $R^{2\dagger}$
Feller-buncher	Number of standing trees	0–13	3.3	185	0.472
	Number of downed trees	0–4	0.7		
	Travel distance (ft)	0–112	15.9		
Skidder	Distance empty (ft)	40–960	418.8	48	0.827
	Distance loaded (ft)	80–1,010	486.9		
	Number of trees	14–41	24.2		
Delimber	Number of sawlogs	0–7	0.9	153	0.023
	Number of post and poles	0–4	0.6		
Processor	Number of sawlogs	0–3	1.0	150	0.214
	Number of post and poles	0–7	0.7		
Loader	Number of logs	1–11	3.8	135	0.154

* 67% of the observed data that were used in model development.
† Developed from the reserved data (33%) for model validation.

strongest correlation (Pearson's correlation coefficient of 0.913) whereas delimber cycle time and number of post and pole logs had the weakest correlation (Spearman's rank-order correlation coefficients of 0.011).

Our delay-free cycle time linear regression models show that the number of standing trees, the number of downed trees, and travel distance are significant predictors for feller-buncher cycle time (Table 5). It was estimated, on average, that one downed tree adds 5.89 s to feller-buncher cycle time whereas a standing tree adds only 2.67 s, indicating that the presence of downed trees is the most influential variable in the model. 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. One additional tree increased the cycle time by 2.34 s on average. Coefficients for empty travel distance and loaded travel distance were estimated as 0.218 and 0.225, respectively. Both processor and delimber cycle time regression models include two independent variables: number of sawlogs and number of post and pole logs. The cycle time regression model for the loader includes only one independent variable (i.e., number of logs). All independent variables were significant ($P < 0.05$) except for the number of post and pole logs in estimating delimber cycle times ($P = 0.1325$).

The ranges of the independent variables and their means are described in Table 6 by machine. The feller-buncher cut and bunched on average 4 trees per cycle, including 3.3 standing trees and 0.7 downed trees. The mean cycle time of the feller-buncher was predicted to be 28.85 s when the means of independent variables were used in the model. Recall that the model was developed using 67% of the observations, with 33% used for validation; therefore, the value is very close to, but not exactly equal to, the mean of all observations shown in Table 4. The means of empty travel distance and loaded travel distance for the skidder were 418.8 and 486.9 ft, respectively. The loaded travel distance was longer than the empty travel distance because the skidder had to maneuver tree piles into a favorable position for the delimber at the landing. On average, the skidder delivered 24.2 trees per cycle, and the mean cycle time was predicted at 219.11 s using the regression model. The average cycle times of the delimber and processor were predicted to be 35.1 and 25.4 s, respectively, when the mean values of the independent variables were used. On average, it took 26.8 s for the loader to load 3.8 logs, which is a rate of 8.5 logs per minute.

Our two-sample *t* test between the validation data (reserved cycle times) and model estimates shows that there is no difference between the data groups (Table 6), supporting the predictive quality of the model. This indicates that the delay-free cycle time regression models could be used for predicting cycle times of the harvesting machines that operate in similar conditions as those at the study site.

Productivity and Costs of the Harvesting System

The loader (50.26 tons hr^{-1}) and feller-buncher (45.00 tons hr^{-1}) showed high productivities compared with the other machines in the system (Table 7). The delimber (17.54 tons hr^{-1}) was the least productive machine because of its slow cycle time and small turn size. The processor (26.78 tons hr^{-1}) had similar turn

Table 7. Average cycle time, average turn size, productivity, and machine rate of each machine.

Machine	Average cycle time* (s cycle^{-1})	Average turn size (ton cycle^{-1})	Productivity† (ton hr^{-1})	Machine rate† (\$ hr^{-1})
Feller-buncher	28.85	0.60	45.00	141.35
Skidder	219.11	3.62	38.68	122.58
Delimber	35.14	0.23	17.54	119.56
Processor	25.39	0.25	26.78	152.58
Loader	26.81	0.58	50.26	66.07

* Delay-free cycle time in seconds.
† Scheduled machine hour.

Table 8. Productivity and unit costs of the observed harvesting system.

Machine	Productivity (ton hr^{-1})* Each	Productivity (ton hr^{-1})* Combined	Unit cost (\$ ton^{-1})
Feller-buncher	45.00	45.00	3.19
Two skidders	38.03	77.36	5.53
Processing		44.32	6.14
Delimber	17.54		
Processor	26.78		
Loader	50.26	50.26	1.49
Overall system	-	44.32	16.35

*Scheduled machine hour.

size but faster cycle times than the delimber, resulting in a higher productivity.

Our machine rate calculations show that the processor was the most expensive machine on a scheduled machine hour basis, followed by the feller-buncher and skidder (Table 7). The loader was the lowest cost machine, mainly because of its low purchase price.

The productivity of the observed harvesting system was estimated at 44.32 tons hr^{-1}, constrained by the processing function that slowed down the entire system (Table 8). The skidding function, with two skidders operating simultaneously, had the highest productivity (77.36 tons hr^{-1}) and was the most constrained function in the observed system (i.e., exhibited the greatest loss of productivity in the system).

The unit production cost of the entire system was estimated at \$16.35 ton^{-1} (Table 8). The processer and delimber are together responsible for 38% of the production cost. Two skidders together and the feller-buncher account for 34 and 20% of the cost, respectively.

Optimal System Configurations

Six alternative system configurations were examined with regards to system productivity and unit cost of timber production (Table 9). System productivity ranged from 35.08 to 45.00 tons hr^{-1} with Configuration 3 being the highest productivity and Configurations

Table 9. Unit production cost of the six system configurations examined.

Configuration 1				
Machine	Productivity (ton hr^{-1}) One	Productivity (ton hr^{-1}) Combined	System productivity (ton hr^{-1})	Unit cost (\$ ton^{-1})
Feller-buncher	45.00	45.00	44.32	3.19
Skidder (2)	38.68	77.36		5.53
Processing		44.32		6.14
Delimber	17.54			
Processor	26.78			
Loader	50.26	50.26		1.49
Overall system	—	—		16.35

Configuration 2				
Machine	Productivity (ton hr^{-1}) One	Productivity (ton hr^{-1}) Combined	System productivity (ton hr^{-1})	Unit cost(\$ to n^{-1})
Feller-buncher	45.00	45.00	38.68	3.65
Skidder (2)	38.68	38.68		3.17
Processing		44.32		7.04
Delimber	17.54			
Processor	26.78			
Loader	50.26	50.26		1.71
Overall system	—	—		15.57

Configuration 3				
Machine	Productivity (ton hr^{-1}) One	Productivity (ton hr^{-1}) Combined	System productivity (ton hr^{-1})	Unit cost (\$ ton^{-1})
Feller-buncher	45.00	45.00	45.00	3.14
Skidder (2)	38.68	77.36		5.45
Processing		53.56		6.78
Processor (2)	26.78			
Loader	50.26	50.26		1.47
Overall system	—	—		16.84

Configuration 4				
Machine	Productivity (ton hr^{-1}) One	Productivity (ton hr^{-1}) Combined	System productivity (ton hr^{-1})	Unit cost(\$ to n^{-1})
Feller-buncher	45.00	45.00	35.08	4.03
Skidder (2)	38.68	77.36		6.99
Processing		35.08		6.82
Delimber (2)	17.54			
Loader	50.26	50.26		1.88
Overall system	—	—		19.72

Configuration 5				
Machine	Productivity (ton hr^{-1}) One	Productivity (ton hr^{-1}) Combined	System productivity (ton hr^{-1})	Unit cost (\$ ton^{-1})
Feller-buncher	45.00	45.00	38.68	3.65
Skidder	38.68	38.68		3.17
Processing		53.56		7.89
Processor (2)	26.78			
Loader	50.26	50.26		1.71
Overall system	—	—		16.42

Configuration 6				
Machine	Productivity (ton hr^{-1}) One	Productivity (ton hr^{-1}) Combined	System productivity (ton hr^{-1})	Unit cost(\$ to n^{-1})
Feller-buncher	45.00	45.00	35.08	4.03
Skidder	38.68	38.68		3.49
Processing		35.08		6.82
Delimber (2)	17.54			
Loader	50.26	50.26		1.88
Overall system	—	—		16.22

Configuration 3 has the highest productivity and Configuration 2 has the lowest production cost.

Table 10. **Changes in unit cost of the six system configurations with varying downed-tree proportions.**

	Configuration					
Downed-tree proportion	1	2	3	4	5	6
0%						
Unit cost ($ ton^{-1})	16.35	15.57	15.44	19.72	16.42	16.22
Bottleneck	Proc.	Skid.	F-b	Proc.	Skid.	Proc.
20% (Observed)						
Unit cost ($ ton^{-1})	16.35	15.57	16.84	19.72	16.42	16.22
Bottleneck	Proc.	Skid.	F-b	Proc.	Skid.	Proc.
40%						
Unit cost ($ ton^{-1})	17.79	15.57	18.60	19.72	16.42	16.22
Bottleneck	F-b	Skid.	F-b	Proc.	Skid.	Proc.
60%						
Unit cost ($ ton^{-1})	19.12	15.88	19.99	19.72	16.75	16.22
Bottleneck	F-b	F-b	F-b	Proc.	F-b	Proc.
80%						
Unit cost ($ ton^{-1})	20.47	17.01	21.40	19.72	17.94	16.22
Bottleneck	F-b	F-b	F-b	Proc.	F-b	Proc.

F-b = feller-buncher, Skid. = skidder, Proc. = processing.

Table 11. **Comparison of unit production costs of the standard operation to one with a buffer to prevent the feller-buncher from becoming a bottleneck in the system.**

	60% Downed-tree proportion (Configuration 2)	
System attribute	Standard	Decoupled
Unit cost ($ ton^{-1})	15.88	15.57
Bottleneck	Feller-buncher	Skidding

4 and 6 being the lowest. The unit cost of production ranged between $15.57 and $19.72 ton^{-1}, and Configuration 2 was the lowest cost system. Configuration 2 used only one skidder while keeping all of 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 better system balance, resulting in a 5% lower production cost than the observed system.

Scenario Analysis on Downed Tree Proportions

The six system configurations were also examined under different site conditions ranging from 0 to 80% proportions of downed trees (Table 10). Configuration 3 was identified as being the most cost-effective when the harvest unit had no downed trees. Configuration 2 became the most cost-effective when the downed tree proportion was between 20 and 60%. The unit production cost of Configuration 2 did not change up to 40% downed trees because the skidder was the system bottleneck. However, the system bottleneck changed from the skidder to the feller-buncher at 60% downed trees, slightly increasing the unit cost from $15.57 to $15.88 ton^{-1}. At the 80% downed tree proportion, Configuration 6 was identified as the lowest cost system ($16.22 ton^{-1}) with the feller-buncher being a system bottleneck.

The feller-buncher is the only machine in these systems affected by the presence of downed trees and can be decoupled from skidders. In practice, this means that the feller-buncher cuts the stand well ahead of the skidder, creating a sufficient production buffer between the two functions. We examined this decoupled operation case for the 60% downed tree scenario in which the feller-buncher became a system bottleneck. As expected, the unit production cost of Configuration 2 decreased by $0.31 ton^{-1} for the 60% downed tree proportion scenario with a change in bottleneck machine to the skidder (Table 11).

Discussion

Effects of Downed Trees on 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. Anecdotally, these results are consistent with most practitioners' experience, with the machine clearly taking more time to handle downed trees than standing trees because of the extra movement of the feller-buncher head. This effect becomes especially severe in stands where fallen trees are horizontal on the ground. The feller-buncher used in this study can rotate its felling head 360° from the horizontal axis and tilt up to 180° from the vertical, allowing it to grasp downed trees without its disc saw contacting the ground. However, as observed, this action adds time and reduces productivity, which can add significant costs to the operation.

The cycle time differences between standing and downed trees are likely to be closely connected to the characteristics of the machine head, especially size, maneuverability and saw type. Feller-bunchers with less maneuverable heads will show more dramatically increased time for harvesting downed or mixed stands compared with the machine used in this study. The continuous disk saw on the feller-buncher head was also presumably a factor, causing an increase of cycle time in handling downed trees. We observed that the operator paid extra care when handling downed trees to avoid hitting the ground with the disc saw. A feller-buncher with either a shear or bar saw might be slower in standing-tree felling but might be more efficient in dealing with downed trees than a disk saw.

Productivity and Costs of Harvesting Systems

The unit production cost of $16.35 ton^{-1} from the observed harvesting system was within the production cost range reported in previous studies (Drews et al. 2001, Luo et al. 2010, Pan et al. 2008). The high productivity of the two skidders (77.36 tons hr^{-1}) in the observed system could not be matched by the other machines, resulting in operational delays when the skidders were idle. When the skidder is the system bottleneck, this is often due to long skidding distances, and two skidders help restore system balance in such

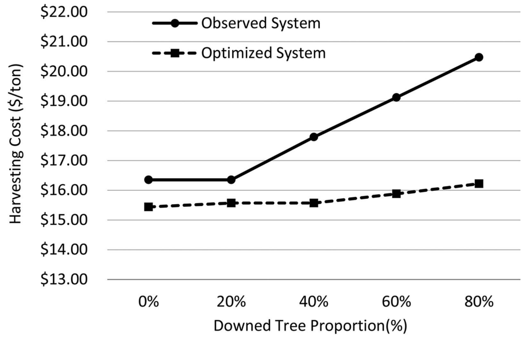

Figure 5. Unit costs before and after the configuration adjustment.

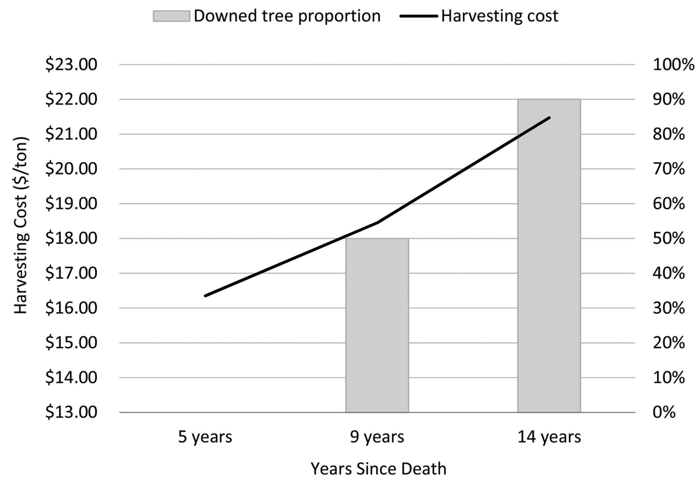

Figure 6. Downed tree proportions versus years since death (data from Mitchell and Preisler 1998) and the estimated harvesting costs of the observed system.

cases. Reducing skidding distances with spur roads and additional log landings is also an option, but it can be costly. In the observed system, as noted previously, one of the skidder operators was new and training on the job, which may explain the contractor's choice to use two skidders for the unit although the skidding distance was relatively short. In addition, because we used the commonly accepted utilization rates of individual machines (Brinker et al. 2002), our estimation of productivity and costs may not exactly match the actual productivity and costs of the harvesting system observed in this study.

The proportion of downed trees in a stand affects the productivity of the feller-buncher. As feller-buncher productivity declines with increased downed trees, the feller-buncher may become a bottleneck, resulting in a lower overall system productivity. Decoupling the feller-buncher from the other machine operations can be a solution to improve the system productivity. In this case, the system is still imbalanced, but additional machine hours on the feller-buncher create a buffer of tree bunches to keep the skidder(s) working at full capacity during their shifts; therefore, operational delays are reduced. It is also worth noting here that because they are more prone to breakage during skidding, tree stems from standing dead and down trees can also result in additional unproductive time and delays for the skidders, which must spend more time clearing breakage from the site, especially if the amount of biomass left on the unit is limited to reduce fire risk. We did not quantify this effect, but we did observe it in the field.

Our results suggest that well-designed harvesting systems tailored to meet specific site conditions and equipment options can be a solution to a challenging harvest unit with a significant portion of beetle-killed trees or trees downed by other disturbance events. Instead of the "one-size-fits-all" approach, observing and reconfiguring a harvest system in response to site conditions can help improve system productivity and reduce production costs. As an example, had the observed system (i.e., Configuration 1) been used in 80% downed tree stands, our study shows that production costs would likely increase by 25.2% compared with the cost of harvesting without downed trees, whereas the cost increase is predicted to be only 5.1% if the system were properly configured for the site conditions (Figure 5). We recognize that loggers frequently face realities that require them to use suboptimal configurations to keep machines and personnel busy and cover fixed costs. Even so, an analysis such as this can help identify opportunities for efficiency gains and improve operations in both the short and long term.

Beetle-Killed Stand Harvesting over Time

Beetle infestation can result in large numbers of dead trees, and those trees are likely to fall on the forest floors over time. Mitchell and Preisler (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 in central Oregon. If the increase of downed trees is a function of time passed after beetle infestation as suggested by Mitchell and Preisler (1998), then our study implies that the longer the decision to salvage harvest is postponed, the more expensive it will be to harvest beetle-killed stands (Figure 6). Furthermore, there is generally 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 (Fraver et al. 2013). Well-timed harvesting in beetle-killed stands may be advantageous in terms of both harvesting costs and value recovery. Depending on management objectives, other benefits, such as the regeneration of favored species and fuel load management, might also increase the value of a timely harvesting decision soon after a disturbance that results in widespread mortality.

Conclusion

It is widely understood by forest managers and industry professionals that stands with high proportions of dead and down trees are generally more costly and less valuable to harvest. This research quantified that effect for a harvest operation in a lodgepole pine stand that suffered high mortality as a result of the mountain pine beetle. Our study suggests that the cost of timber production increases as the proportion of downed trees increases in a beetle-killed stand, mainly because of slower cycle times of the feller-buncher. Our study also suggests that site-specific, well-designed harvesting systems used to respond to beetle-killed stand conditions may counteract the cost increase attributed to higher proportions of downed trees.

The field data used in this research were collected on a single harvest; therefore, a limited range of input conditions were reflected in the developed machine cost and productivity prediction models. However, the prediction models developed and the associated analysis performed in this study provide forest managers and practitioners with useful insights about how downed trees may change the cost structure of a harvesting system, allowing them to identify current barriers and opportunities for improvement. We also hope that this study helps stakeholders understand the potential impact of delayed stand management decisions on harvesting costs and outcomes and provides a benchmark for continued research to define and quantify the costs and benefits of alternative approaches to tackling daunting forest management challenges related to insects, fire, and other landscape-scale disturbances.

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