PRODUCTIVTY AND COST OF A CUT-TO-LENGTH COMMERCIAL THINNING OPERATION IN A NORTHERN CALIFORNIA REDWOOD FOREST

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A Thesis Presented to

The Faculty of Humboldt State University

In Partial Fulfillment of the Requirements for the Degree

Master of Science in Resources: Forestry, Watershed, & Wildland Sciences

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May 2018

ABSTRACT

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Cut-to-length (CTL) harvesting systems have recently been introduced to the redwood forests of California's north coast. These machines are being used to commercially thin dense redwood (*Sequoia sempervirens*) stands which tend to form clumps of stems that vigorously sprout from stumps after a harvest. One of the challenges is to avoid damaging residual trees which can decrease productivity, increase costs, and lower the market value of trees. The goal of this study was to evaluate the productivity and costs associated with CTL systems used in a redwood forests and use that data to develop equations for predictions. Time and motion study methods were used to calculate the productivity of a harvester and forwarder used during the winter and summer seasons. Regression equations for each machine were developed to predict delay-free cycle (DFC) times. Key factors that influenced productivity for the harvesters was tree diameter and distance between harvested trees. Productivity for the harvesting ranged from 28.8 to 35.6 m^3 per productive machine hour (PMH). For the forwarders, the number of logs per load and travel distance were important factors affecting productivity. Forwarder productivity ranged from 22.4 to 23.3 m^3 per PMH. Total stump-to-truck costs for CTL

harvesting system ranged from US$17.1 to $22.8 per m^3.

ACKNOWLEDGEMENTS

I would like to thank my major professor, Dr. Han-Sup Han for his help in organizing study ideas and developing my technical writing skills. I also would like to thank Dr. Pascal Berrill and Dr. Dan Opalach for their advice and guidance as members of my graduate committee. I wish to thank stockroom manager, George Pease for letting me use study equipment during the study and my colleagues, Joel Bisson, Andrew Mueller, Jacqueline Garcia, Garrett Larue, Marinna Gomes, and Kevin Soland for helping me to collect field data.

I wish to thank Green Diamond Resource Company, especially Mike Carroll for using their forest for the study and Miller logging company and machine operators, Darrold, George, and Jose for letting me conduct research during their harvesting operations. This project was funded by the Agricultural Research Institute, California State University: Award number 17-06-004.

Finally, I want to thank my family and girlfriend Sun-hwa Park for their support, love, and encouragement during my time at the Humboldt State University. I would like to thank my friends in Humboldt county and South Korea for their support.

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INTRODUCTION

The interest in cost effective mechanized harvesting systems has increased throughout the Pacific Northwest. Small size stands, with an average diameter of <50 cm, increasingly contribute to the timber supply (Kellogg et al. 1992). These systems provide consistent and high-quality merchantable logs, smaller crew sizes, and a safer work environment compared to traditional harvesting methods (Jarmer and Kellogg 1991). Cut-to-Length harvesting systems, which comprise of a harvester and forwarder, have been increasingly used for thinning stands on gentle terrain in the Pacific Northwest. They handle small-diameter stems very efficiently, provide a safe and enclosed working environment plus they consistently produce high-quality end products at a reasonable cost (Kellogg et al. 1992). These systems differ from conventional mechanized methods like the whole-tree harvesting method. The harvester fells, processes and bucks the stems at the stump while the forwarder transports the processed logs to the landing area (Bettinger and Kellogg 1993). Residual limbs and tops produced from the delimbing process will eventually decay and provide nutrients to the site, and adverse soil impacts will be minimized due to the mat of deposited residual material between the machines and the ground (Hartsough et al. 1997). In addition, CTL requires less labor, road construction, and fewer landing areas (Kellogg and Bettinger 1994).

Cut-to-Length harvesting productivity and cost are affected by stand and harvesting variables, such as tree size and extraction distance (Kellogg and Spong 2004). Many previous studies confirm that tree size is the most significant variable affecting felling productivity (Kellogg and Bettinger 1994; Kellogg and Spong 2004; Adebayo et al. 2007). The average diameter at breast height (DBH) significantly affects the felling and bunching time per tree, which influence the productivity (Lanford and Stokes 1995). The bigger the tree sizes, the more time for felling and processing. One study found that the productivity of felling machines increase as the tree size increases and decrease as the distance between harvested trees increases (Li et al. 2006).

Extraction cycle time differs significantly among machines and extraction distances; extraction productivity increases as the pay load size increase and decreases as the average extraction distance increases (Li et al. 2006). Nurminen et al. (2006) found that timber volume at the loading stop explains nearly 60% of the variation in the time consumption. Loading stop represents the point where a forwarder stops to load additional logs on the bunk. Another study found that load size did not affect travel time, thus there was no difference in the amount of time if the forwarder was traveling empty or traveling loaded (Lanford and Stokes 1995).

Felling coast redwoods (*Sequoia sempervirens*) are a challenge for harvesting operations in the Pacific Northwest. Generally, redwoods regenerate by numerously and vigorously sprouting from stumps and root crowns after harvesting which makes it a relatively unique species among the conifers (Olson et al. 1990). This ability to sprout from the stump is typically observed in the young-growth redwood forest over many thousands of acres in the redwood region (California Department of Forestry and Fire Protection 1990). Sprout clumps self-thin over time, so there will be more stems in clumps thinned at earlier ages (O’Hara and Berrill 2010). These clumps could impede the ability of the harvester head to grab and position a stem. At the same time, harvester should avoid damaging the residual clump to ensure the highest future returns.

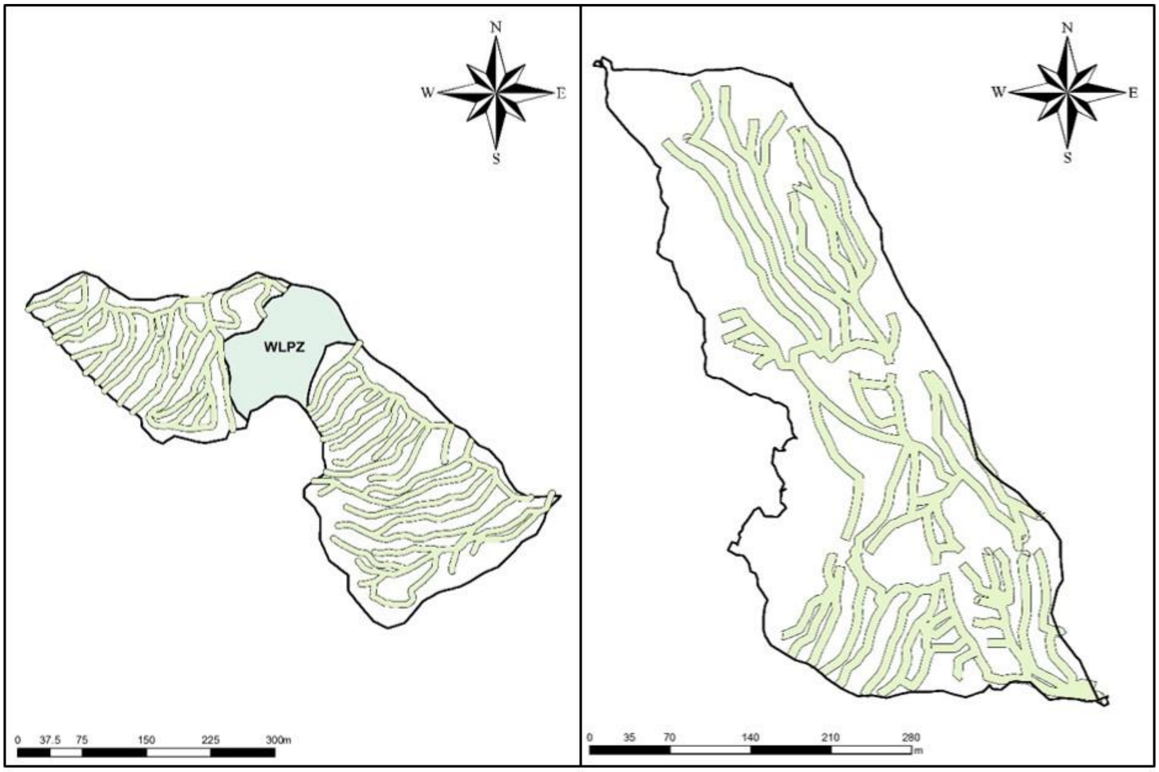
On gentle ground, the many local redwood forest managers use a ground-based system that includes a feller-buncher and shovel loader. Instead of using a skidder or tractor to extract the logs, they prefer to use shovel loader because it has a wider track which minimizes soil disturbance and compaction. Moreover, a change in federal policy and land use management, which criticize for the potential impact to water quality and aquatic resources, increased the interest of alternative harvesting systems in the redwood forests of northern California. To optimize the economic return and reduce impacts on the environment, forest managers are using CTL systems in the redwood forests of Humboldt County for the first time. In many previous studies, productivity and costs of CTL systems have been studied for other conifer plantations such as Douglas-fir (*Pseudotsuga menziesii*), lodgepole pine (*Pinus contorta*), and Norway spruce (*Picea abies*) (Kellogg and Bettinger 1994; Eriksson and Lindroos 2014; Apăfăian et al. 2017). No attempt has been made to study redwood species with CTL system. Evaluation of the productivity and costs of the new harvesting system will be important to land managers to ensure the highest rate of return of their timber.

This study provide basic information on the productivity and cost of a CTL system applied in thinning of young-growth redwood forests in northern California. *The hypothesis is that thinning redwood clump could affect productivity and cost of CTL system. The objectives of this study are to 1) determine productivity (m*^{3}*/hour) and costs ($/m*^{3}*) of CTL systems for thinning operations, 2) evaluate key harvesting and stand* *variables affecting thinning operations in redwood forests, and 3) develop predictive regression equations for CTL systems and use them to assess similar conditions in third-growth redwood forests.*

MATERIALS AND METHODS

Study area description and thinning treatments

The study sites were located on commercial timberlands near the former settlement town of Crannell, California (**Figure 1**). Two study units were characterized as third-growth (25-35 years-old) stands of redwood trees which naturally sprouted from stumps from the previous even-aged harvest that had been clear-cut during the mid-1980s. The dominant species was redwood with small components of coast Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*), red alder (*Alnus rubra*), and Sitka spruce (*Picea sitchensis*). To collect pre-harvesting stand inventory data, 25 to 30 circular sampling plots were laid out in each unit before harvesting operations begun. From each plot, species, DBH, tree height, number of clumps, and the percent slope were recorded to estimate the average stand characteristics. Plot centers were flagged with ribbon and recorded with a global positioning system (GPS), and the plot boundaries were sprayed with paint. This method allowed for re-measurement of the same plots for post-harvesting inventory data after all operations were completed. The two study units were relatively similar in their stand characteristics (**Table 1**). The stand of Unit A was a 10.1-ha with an average DBH of 20.3 cm. The stand of Unit B was a 12.1-ha with an average DBH of 20.9 cm. The average value of DBH in the two units was statistically different ($p<0.05$). The average slope was 1º (1%) for Unit A and 5º (8%) for Unit B. The objective of stand prescription in Unit A was to reduce fuel continuity and increase quadratic mean diameter in the remaining stand. The objective of commercial thinning in Unit B was to retain high quality crop trees, and harvest the trees that are impeding the growth of these retained crop trees.



Unit A Unit B

Figure 1. Study site boundary and forwarder trail at Unit A (10.1-ha) and Unit B (12.1-ha), Crannell, Humboldt County, northern California.

Table 1. Pre-and post-thinning descriptions of stand characteristics at Crannell sites, California.

	Unit A		Unit B	
Characteristics	Pre-thinning	Post-thinning	Pre-thinning	Post-thinning
Average DBH[a] (cm)	20	23	21	28
Average height (m)	20	19	19	19
Average # of stems per clump	6	3	6	2
Average basal area (m^2/ha.)	99	40	92	40
Trees per ha	2393	769	1970	509
Species composition (%)				
redwood	77 (1850)[b]	79 (606)	61 (1198)	73 (371)
red alder	17 (394)	15 (113)	17 (336)	11 (54)
Douglas-fir	5 (114)	4 (34)	10 (188)	9 (48)
Sitka spruce	1 (14)	2 (17)	13 (248)	7 (37)

[a] diameter at breast height.

[b] trees per ha.

Thinning treatment prescription in redwood stand

The objective in Unit A was to reduce the vertical continuity of vegetative fuels and the horizontal continuity of tree crowns and to retain the most healthy and vigorous dominant and codominant trees to achieve 490 or less trees per ha. This prescription kept the slash height on the ground below 46 cm which was generated by the harvester's processing. The Unit A study was conducted during the winter season (January–February, 2017). The objective in Unit B was to retain high quality residual trees and harvest the trees that are impeding the growth of these retained crop trees. This reduced stand density and will promote the growth of residual trees in the post-harvest stand. Unit B operation was performed during the summer (June–July, 2017).

Harvesting system and operations

In Unit A, a single-grip harvester (Ponsse Bear 8-wheel) with a H8 processing head, which has a maximum cutting diameter of 80 cm, was used to fell, delimb, and buck the trees. This harvester has a 240-kW engine and a total weight of 240kN [24 tonnes]. The eight-wheeled forwarder (Ponsse Buffalo 8-wheel) was used for forwarding the logs to the landing area and loading logs onto the truck, instead of adding another loader. The total load capacity for the forwarder is 147kN (15 tonnes) with balanced bogies. All the machines used in both units were fitted with bogie tracks on the front and rear tires while they operated. The operation had a two-day gap between the harvester and the forwarder activities to provide a safe working environment and to optimize the production rate for each machine.

The forwarding and loading operations were decoupled; once the forwarder piled a sufficient amount of logs on the landing site over two to three days, then the forwarder stopped forwarding and loaded the logs onto three trucks over one day. These trucks hauled the logs to the mill. The harvester operator had driven different harvester models, which was made by a different manufacturer, and had over 20 years of experience working with the Ponsse Bear in redwood forests. He felled the trees based on the prescription and his judgement. The forwarder operator had six months of experience. The harvester produced logs length between 3.05 m and 8.13 m with average of 5.83 m plus trim allowance (15 cm) for fence wood.

In Unit B, a different single-grip harvester (Ponsse Ergo 8W) with a H7 head model, which has maximum cutting diameter of 72 cm, was used by a different operator. This machine has a 205-kW engine and a typical weight of 210kN (21 tonnes). The same operator and forwarder models were used in Unit B. The forwarding and loading operations were coupled; when the forwarder saw the truck coming, or radio communicated with the hauling truck driver, the forwarder stopped forwarding, moved to the landing site, and started loading logs onto the truck. In this unit, one truck was used to haul the logs. The harvester operator had five years of experience with a different harvester and two months of experience working in redwood forests. The forwarder operator had 10 months of experience in similar terrain. The log lengths produced by the harvester were between 3.17 m and 8.11 m with average of 5.72 m with trim allowance (15 cm).

This study was observational in nature as opposed to a replicated research study. Therefore, Units A and B had different stand conditions, thinning treatments, and felling/processing methods.

Data collection and analysis

A time study was conducted to determine felling, processing, forwarding, and loading productivity. All activities associated with the harvester and forwarder operations was divided into defined time elements (**Table 2**) and recorded in centi-minutes using a stopwatch. The cycle activity for the harvester was considered as felling and processing one tree to merchantable logs. In Unit A and B, 300 and 350 trees, respectively, were randomly selected. These trees were numbered with tape and DBH, species, height, and number of trees in the clump were recorded before the felling operation began. The harvester cycle time and independent variables were recorded by one person riding in the cab.

Table 2. Felling/processing and forwarding elements, delays and their descriptions.

Elements	Definition
Harvester	
Move	Starts when the harvester begins traveling to its desired position. The time ends when the harvester stops traveling and begins moving the head.
Fell	Starts when the boom moves and grabs the tree and cut. Ends when treetop hits the ground.
Process	Starts when the head starts to process the tree, and ends when the tree has been completely processed.
Top bucking	Starts when the head saw bucks the unmerchantable tree-top and ends when the operator is ready to begin the next task.
Brushing	Starts when head saw cuts and processes saplings to produce slash on the trail. This does not make merchantable logs.
Forwarder	
Travel empty	Starts when the forwarder begins traveling with empty bunk, and ends when the forwarder stops traveling and begins moving the crane.
Loading	Starts when the forwarder begins moving crane, and ends when the forwarder loads the logs into the bunk.
Travel loading	Starts when the forwarder begins traveling with loaded bunk. Ends when the forwarder stops traveling and begins moving the crane.
Arrangement	Starts when the grapple lets the logs, and ends when the grapple begins next moving.
Travel full	Starts when the forwarder fixes the crane on the fully loaded logs and begins traveling with fully loaded bunk, and ends when the forwarder stops traveling and begins moving crane.
Bunk to deck	Starts when the forwarder begins moving crane, and ends when the forwarder unloads the logs from the bunk to the deck.
Delays	
Mechanical	Non-harvesting time occurring because of the machine
Personal	Non-harvesting time associated with the operator
Operational	Non-harvesting time occurring because of operational influences to the production system.

Log scaling was conducted with Smalian's formula to get an average log volume (m^3) for estimating hourly thinning productivity of the harvester and forwarder. The forwarder used the trails that were made during the harvester operation. Before forwarding operation began, the trails were divided into 10 m lengths and painted on stumps and residual trees. The forwarding and loading cycle time and independent variables were collected by one person from a safe distance.

All the collected time study data were entered in Microsoft Excel. Multiple linear regression analysis was performed using R program (R Core Team 2014) using the MASS (Venables and Ripley 2013) and car (Fox and Weisberg 2011) packages to develop equations for predicting delay free cycle (DFC) time for thinning operations. Dummy variables were used for representing species and clump existence. To assure the assumptions of the Ordinary Least Squares regression, normality and homogeneous variance of residuals, Durbin-Watson test, and variance inflation factor (VIF) were used. Several models were transformed to meet assumptions. Multi-collinearity between independent variables was tested using a threshold of VIF less than 10. Final models were selected using the backward elimination method. To validate the developed regression equations, the original data was randomly partitioned into k equal folds; each fold was retained as the reserved data; k-1 folds were used as trained data. Then, the model was tested to predict the cycle time for one reserved fold. The process was repeated k times; each of the folds were used once as the validated data. Ten-fold cross-validation was used in this study, which is generally used, except loader for the 3-fold method because of the lack of data.

The standard machine rate calculation method (Miyata 1980) was used to estimate hourly machine costs in US dollars per scheduled machine hour ($/SMH; **Table 3**). Machine purchase price, economic life, wages and benefits of the workers were collected from the dealer and contractor. Operator wage was set at $26.00 per hour for harvester and $24.00 per hour for the forwarder with 32% in fringe benefits. All machinery was set to a 5-years economic lifespan with 2,000 SMH per year. Salvage value, interest, insurance, maintenance, repair, and lubrication were assumed based on a study of Brinker et al. (1989). The salvage value and interest was set at 20% and 8%, respectively. Hourly fuel consumption was calculated based on machine engine power. Diesel price was estimated from the local market price during the study. Because of different initial prices of the harvesters, hourly machine costs of Unit A were higher than those of Unit B.

Table 3. Input values and assumptions used for calculation of hourly machine cost ($/PMH) for a CTL harvesting system.

Machine Input	Harvester (Unit A)	Harvester (Unit B)	Forwarder
Model	Ponsse Bear 8W	Ponsse Ergo 8W	Ponsse Buffalo 8W
Purchase Price ($USD)	750,000	550,000	490,000
Salvage Value (%)	20	20	20
Economic life (years)	5	5	5
Hours per year (SMH[a]/year)	2,000	2,000	2,000
Interest (%)	10	10	10
Insurance (%)	4	4	4
Taxes (%)	2	2	2
Horse power	322	275	275
Fuel use rate (gal/PMH[b])	11.9	10.2	10.2
Lube cost (% of fuel cost)	36.8	36.8	36.8
Maint. & Repair (%)	100	100	100
Wages ($USD/hr)	26	26	23.75
Fringe benefits (%)	32	32	32
Utilization (%)[c]	80	80	80
Hourly cost ($/SMH)	232.7	183.6	164.2
Hourly cost ($/PMH)	290.8	229.5	205.3

[a] scheduled machine hour.
[b] productive machine hour.
[c] referenced from Brinker et al. (1989).

RESULTS

Felling and processing productivity

In Unit A, a total 1,132 trees were felled and processed by the harvester and were analyzed to summarize descriptive statistics for the variables and cycle element times (**Table 4**). The average DFC time was 57.9 seconds per tree, resulting in an average productivity of 28.8 m^3 per PMH (**Table 7**). Average DBH for the harvested trees was 24.5 cm. The average produced volume per tree was 0.46 m^3 and ranged from 0.12 to 1.04 m^3, excluding the volume of the tree-tops. The most time-consuming elements were felling and processing, requiring approximately 58% of the total DFC time. The proportion of time for brushing was 23%. Distance moved between harvested trees averaged 1.9 m; moving accounted for a small proportion (9%) of the total DFC time because felling and processing for several trees occurs at one stop.

Table 4. Summary of average felling/processing cycle elements and independent variables that were collected to evaluate the productivity of harvester used in a cut-to-length thinning.

Felling/processing Cycle elements	Unit A[a] Average time (seconds)	Percent (%)	Unit B[b] Average time (seconds)	Percent (%)
Move	5.0 (8.4)[c]	8.7	3.9 (11.4)	6.7
Fell	17.9 (7.6)	30.9	16.8 (8.0)	28.4
Process	15.7 (10.2)	27.1	22.1 (23.1)	37.3
Top	5.8 (2.5)	10.0	5.0 (2.8)	8.5
Brush	13.5 (21.3)	23.3	11.3 (21.7)	19.1
Delays	9.1 (25.9)	-	8.6 (37.4)	-
Average DFC	57.9 (27.6)	100.0	59.2 (36.9)	100.0
Independent variables	**Average**	**Range**	**Average**	**Range**
Distance (m)	1.9 (3.8)	0 – 64	1.5 (6.1)	0 – 156
Species[d]	1.2*	0 – 4	1.9*	0 – 4
DBH[e] (cm)	24.5 (7.1)	15 – 56	24.1 (7.0)	10 – 64
Clump[f]	0.8	0 – 1	0.5	0 – 1
# of logs	1.6 (0.6)*	1 – 3	1.9 (0.7)	1 – 5
# of top cuts	2.1 (1.1)	0 – 6	1.5 (1.0)	0 – 6

[a] sample size = 1132 trees.
[b] sample size = 1486 trees.
[c] values in ( ) indicate standard deviation.
[d] 1 = redwood, 2 = red alder, 3 = Douglas-fir, 4 = Sitka spruce.
[e] diameter at breast height.
[f] 1 = clump tree, 0 = individual tree.
[*] not a significant variable.

Most of the observed delays (50%) were operational delays such as tree hang-ups, obstacle removal, and log arrangement (**Table 6**). Mechanical delays, such as chain and bar problem and machine maintenance, accounted for 22% of observed delays. The remainder of the delay times were personal delays, such as lunch and restroom breaks. Utilization (87%) was estimated based on observed small delay times less than 15 minutes during the study.

In Unit B, a total of 1,486 trees were felled and processed by the harvester. The harvester had an average completion time of 59.2 seconds per tree, resulting in an average productivity of 35.6 m^3 per PMH. Average DBH for the harvested trees was 24.1 cm. The average log volume per tree was 0.59 m^3 and ranged from 0.12 to 1.51 m^3, excluding the volume of the tree-tops. Felling and processing accounted for 66% of the total DFC time. The harvester consumed 19% of the total DFC time for brushing. A small portion of total DFC time accounted for moving, with an average distance of 1.5 m.

The proportion of observed delays for operational delays was 52% of the total time. A substantial portion was attributed to mechanical delays (32%). Personal delays constituted a small proportion (16%) of the total observed delays. Utilization percentage for the harvester was 87%.

Forwarding and loading productivity

In Unit A, a total of 27 forwarding cycles and 13 loading observation cycles were recorded during the study (**Table 5**). The average forwarding DFC time per load was 55.4 minutes. Loading was the most (50%) time consuming element of the forwarding cycle time. The average number of logs produced per cycle was 78 and varied from 56 to 157. The forwarder extracted an average of 28.6 m^3 per cycle and produced 22.4 m^3 per PMH. The loader loaded an average of 104 logs onto the truck over an averaged productivity of 58.9 m^3 per PMH; and took 30.8 minutes of DFC time to complete.

The proportion of observed delays for personal delays was 68%, operational delays 22%, and mechanical delays 11%. Utilization percentage for the forwarder was 91% at Unit A.

Table 5. Summary of average forwarding cycle elements and independent variables that were collected to evaluate the productivity of forwarder used in a cut-to-length thinning.

Forwarding Cycle elements	Unit A[a] Average time (minutes)	Percent (%)	Unit B[b] Average time (minutes)	Percent (%)
Travel empty	2.7 (2.2)[c]	4.9	2.6 (2.7)	7.4
Load	27.5 (7.4)	49.6	14.2 (5.7)	40.5
Arrangement	8.2 (6.8)	14.8	4.7 (2.9)	13.1
Travel loading	6.5 (3.9)	11.8	6.7 (3.6)	19.0
Travel full	2.5 (1.4)	4.5	2.3 (1.8)	6.4
Unloading	8.0 (3.0)	14.4	5.2 (2.4)	13.6
Delays	4.4 (3.7)	-	3.9 (6.8)	-
Average DFC	55.4 (19.5)	100.0	35.1 (12.1)	100.0
Independent variables	**Average**	**Range**	**Average**	**Range**
EDT[d](m)	96.4 (64.7)*	20 – 280	92.8 (89.0)*	6 – 459
LDT[e](m)	133.6 (86.1)	26 – 378	166.4 (106.5)*	9 – 470
FDT[f](m)	88.2 (56.0)*	8 – 197	74.4 (61.2)	6 – 233
# of logs	78.1 (19.6)	56 – 157	51.8 (22.9)	9 – 102

[a] Sample size = 27 and 13 observations for forwarding and loading, respectively.
[b] Sample size = 39 and 15 observations for forwarding and loading, respectively.
[c] values in ( ) indicate standard deviation.
[d] empty moving distance.
[e] loaded moving distance.
[f] fully loaded moving distance.
[*] not a significant variable.

In Unit B, a total of 39 cycles for forwarding and 13 cycles for loading observations were recorded (**Table 5**). The average DFC time per load was 35.1 minutes and accounted for most (41%) of the forwarding delay-free time. The forwarder forwarded an average of 13.6 m^3 per cycle; the average number of logs produced per cycle was 50 and ranged from 9 to 102. The forwarder produced 23.3 m^3 per PMH. The loader averaged 99 logs loaded onto the truck over an average time of 25 minutes. This loader produced 72.9 m^3 per PMH.

The largest delays were operational delays (38%), and the substantial proportion of total delay times was mechanical delays (36%). Personal delays (27%) accounted for the rest of the total delay time at Unit B. Percent utilization of the forwarder was 90% based on observed small delays.

Table 6. Summary of delays and utilization rates for CTL harvesting machines

	Unit A			Unit B		
	Frequency	Average time	Percent[a]	Frequency	Average time	Percent
Machine/delay type	(n)	(minutes)	(%)	(n)	(minutes)	(%)
Harvester						
Mechanical[b]	26	2.17	22.2	47	2.48	32.4
Operational[c]	526	0.24	49.1	608	0.31	51.7
Personal[d]	83	0.88	28.7	125	0.45	15.8
% utilization[e]			86.4			87.0
Forwarder						
Mechanical	9	2.05	15.5	7	7.73	31.3
Operational	82	0.45	30.8	43	1.60	46.5
Personal	91	0.70	53.7	19	1.83	22.3
% utilization			92.7			90.2
Loader(forwarder)						
Mechanical	3	8.13	13.3	2	2.53	2.5
Operational	68	2.09	76.3	67	2.76	91.4
Personal	27	0.70	10.4	21	0.59	6.1
% utilization			68.6			65.0

[a] percent of total delay time for a specific machine based on weighted average.

[b] mechanical delay includes chain problems, harvester head roller problem, machine maintenance, and machine break down.

[c] operational delay includes tree hang-ups, stump removal, brushing, and waiting at the landing (e.g. forwarder waiting for log truck).

[d] personal delays include lunch time, personal time, and talks not relevant to work.

[e] percentage utilization based on delay-free cycle time and observed small delays less than 15 minutes.

Table 7. Average (standard deviation) of delay-free cycle times and harvesting productivity (m^3/PMH) observed for a cut-to-length thinning in redwood forests.

Machines	Average DFC[a] time (minutes)	Turn Piece (# pieces/cycle)	Turn size (m^3/cycle)	Harvesting productivity (m^3/PMH[b])
Unit A				
Harvester	1.0 (0.5)[b]	2 (0.6)	0.5 (0.2)	28.8
Forwarder	55.4 (19.5)	78 (21.2)	20.7 (8.2)	22.4
Loader(Forwarder)	30.8 (12.8)	104 (11.0)	30.2 (2.5)	58.9
Unit B				
Harvester	1.0 (0.6)[c]	2 (0.7)	0.6 (0.3)	35.6
Forwarder	35.1 (12.1)	49 (22.9)	13.6 (7.3)	23.3
Loader(Forwarder)	25.0 (3.5)	99 (16.2)	30.4 (3.7)	72.9

[a] delay-free-cycle.
[b] productive machine hour.
[c] values in ( ) indicate standard deviation.

Thinning production equations

The productivity equations for all harvesting machines developed based on the time study data over all the associated variables (**Table 8**). Harvester cycle time was influenced by all variables significantly, except species. The number of logs per tree was not found to be significant in determining harvester cycle time at Unit A. The number of logs per forwarding cycle was significant in determining DFC time for forwarder at both units. Travel distance during loading was significant for the forwarder in Unit A. whereas, travel distance while fully loaded was not significant but contributed to a small portion to DFC time for the forwarder in Unit B.

Table 8. Productivity equations developed for predicting delay-free cycle time of a cut-to-length harvesting machines in young growth redwood forests.

		Average cycle time estimator		r^2	r^2	
Machines		(centi-minutes)	*p*-value	Adjusted[a]	Validated[b]	n
Unit A						
Harvester	DFC$^{-0.2}$	= 4.6278E-01 - 5.0899E-03 * (Distance) - 1.2159E-03 * (DBH) - 8.6847E-03 * (Clump)[c] - 3.5958E-03 * (# of top cuts)	< 0.0001	0.24	0.23	1128
Forwarder	DFC^{-1}	= 3.563E-04 - 3.177E-07 * (Loaded travel distance) - 1.496E-06 * (# of logs)	< 0.05	0.75	0.63	27
Loader (forwarder)	DFC$^{0.2}$	= 0.976198 + 0.357502 * (Move)[d] + 0.036627 * (# of logs)	< 0.05	0.97	0.97	12
Unit B						
Harvester	DFC$^{-0.25}$	= 4.2017E-01 - 2.9174E-03 * (Distance) - 2.2850E-03 * (DBH) - 7.4599E-03 * (Clump) - 7.7407E-03 * (# of logs) - 7.6267E-03 * (# of top cuts)	< 0.0001	0.30	0.29	1480
Forwarder	DFC	= 978.868 + 3.467 * (Fully travel distance) + 41.847 * (# of logs)	< 0.0001	0.68	0.63	35
Loader (forwarder)	DFC	= 2499.9	-	-	-	15

[a] adjusted r^2 developed from total observed data.

[b] validated r^2 developed from 10-fold cross validation; except loader for 3-fold cross validation due to a small number of samples.

[c] 1 if clump tree; otherwise 0.

[d] 1 if move; otherwise 0.

Stump to truck cost

The stump-to-truck costs for CTL harvesting was \$22.80/m^3 and \$17.10/m^3 in Unit A and Unit B, respectively (**Table 9**). These costs excluded move-in/out and support vehicle costs, overhead, and profit-and-risk allowance. The harvesting cost for each machine was calculated by dividing the hourly machine cost with hourly production. The felling and processing cost of \$10.10/m^3 contributed large proportion (44%) of the total harvesting cost at Unit A. The primary transportation cost of logs from the stump to landing by the forwarder was \$8.80/m^3 and represented a sizeable proportion (49%) of the total harvesting cost in Unit B.

Table 9. Stump-to-truck cost (\$/m^3) of cut-to-length thinning in young redwood stand in northern California.

Machines	Machine cost (\$/PMH[a])	Hourly production (m^3/PMH)	Harvesting cost (\$/m^3)	Percent of total cost (%)
Unit A				
Harvester	290.8	28.8	10.1	44.4
Forwarder	205.3	22.4	9.2	40.3
Loader (Forwarder)	205.3	58.9	3.5	15.3
Total	701.4	-	22.8[b]	100.0
Unit B				
Harvester	229.5	35.6	6.4	35.6
Forwarder	205.3	23.3	8.8	48.8
Loader (Forwarder)	205.3	72.9	2.8	15.6
Total	640.1	-	17.1	100.0

[a] productive machine hour.

[b] these cost does not include move in/out cost, overhead, profit-and-risk allowance.

Standardization

To evaluate the harvesting cost for CTL thinning more evenly, standardized values were used in developed equations from time study and stand data on both units (Error! Reference source not found.). Values of the variables for the harvester was 1.7 m for the moving distance, 24.3 cm for DBH, 0.62 m^3 for volume per stem, 1 for clump trees, 2 logs, and 2 times for top bucking. The forwarder's values of the variables were 150 m for moving distance while loading, 81.3 m for moving distance with fully loaded, 0.28 m^3 for log volume, and 65 logs. The variables for loader with 1 for moving time occurred, 0.28 m^3 for log volume, and 102 logs were used in the equation for Unit A.

Table 10. Standardized[a] felling/processing, forwarding and loading, and stump-to-stuck cost ($\$/m^3$) of cut-to-length thinning for young redwood stand in northern California.

Site	Harvester	Forwarder	Loader	Stump-to-truck	Harvesting cost[b]	Difference[c]
Unit A	6.9	4.6	4.0	15.5	22.8	-32.0%
Unit B	5.8	7.5	3.0	16.2	17.1	-5.3%

[a] standardized values of the varaibles were average of moving distance (1.7 m), DBH (24.3 cm), clump tree, number of logs per stem (2 logs), number of top bucking (2 times), travel loading distance (150 m), travel full distance (81.3 m), number of logs per forwarding cycle (65 logs), loader move occurred, and number of logs per loading cycle (102 logs).

[b] observed stump-to-truck costs.

[v] differences in percentage of the observed harvesting cost over the standardized stump-to-truck cost.

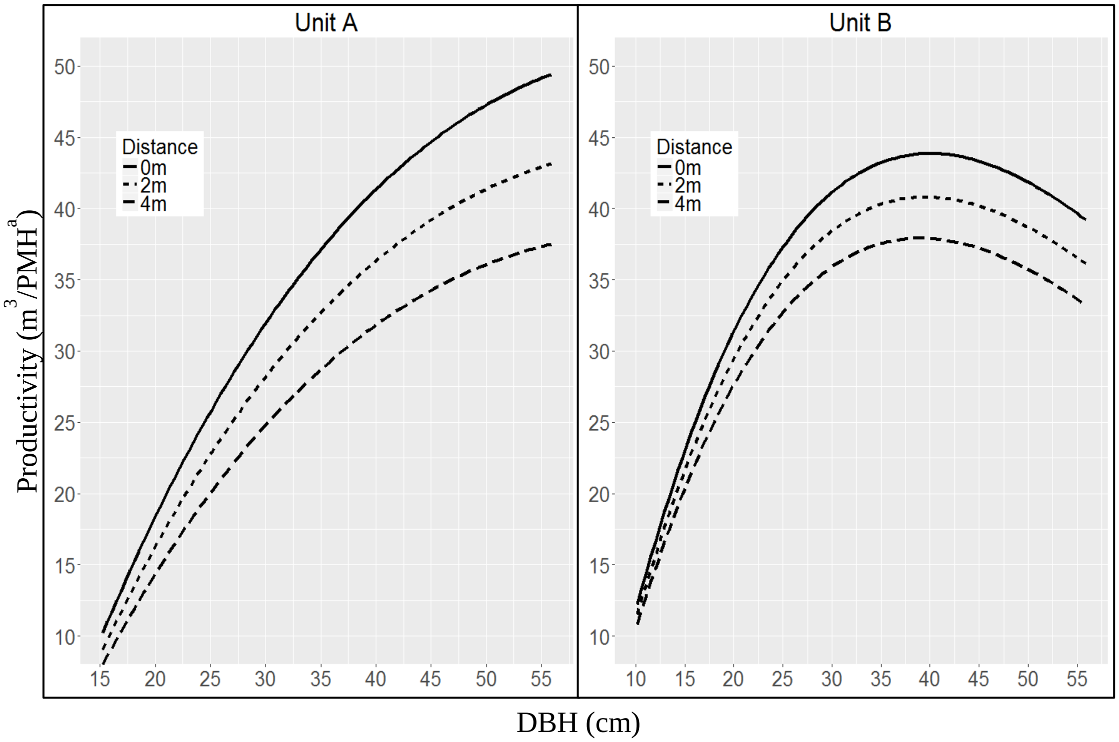
The standardization reduced the stump-to-truck costs for CTL thinning in both units. In Unit A, standardization decreased 32% of the stump-to-truck cost from the observed average value of $\$22.80/m^3$ to standardized value of $\$15.5/m^3$. Harvester thinning cost decreased as moving distance decreased and DBH increased. Forward cost was affected by standardization. In Unit B, stump-to-truck cost was less changed by standardization compared to Unit A. The standardization decreased 5.3% from \$17.10 to \$16.20 per m^3 of stump-to-truck costs. The standard values for harvester, forwarder, and loader were similar to observed average costs.

DISCUSSION

The objective of this study was to evaluate key harvesting and stand variables affecting CTL thinning operations in young third-growth redwood stands, where the trees commonly formed a clump rather than to compare the two units. The results showed that a CTL harvesting system can be efficiently used to thin similar stand conditions in young third-growth redwood stands, where the trees commonly form a clump. Furthermore, the results are valid with appropriate weather condition in the summer and winter seasons.

Felling and processing operations

Generally, tree size (Kellogg and Spong 2004), such as DBH was the significant factor affecting productivity in felling and processing operations. The productivity of the harvester increased as the tree DBH increased (Error! Reference source not found.). However, compared with the result of Unit A, the productivity of the harvester in Unit B decreased when felling trees over 40 cm of DBH. Due to the different machine power and head size, the harvester head dropped and re-grabbed large trees several times while processing. This increased time consumption for processing resulted in decreased productivity.

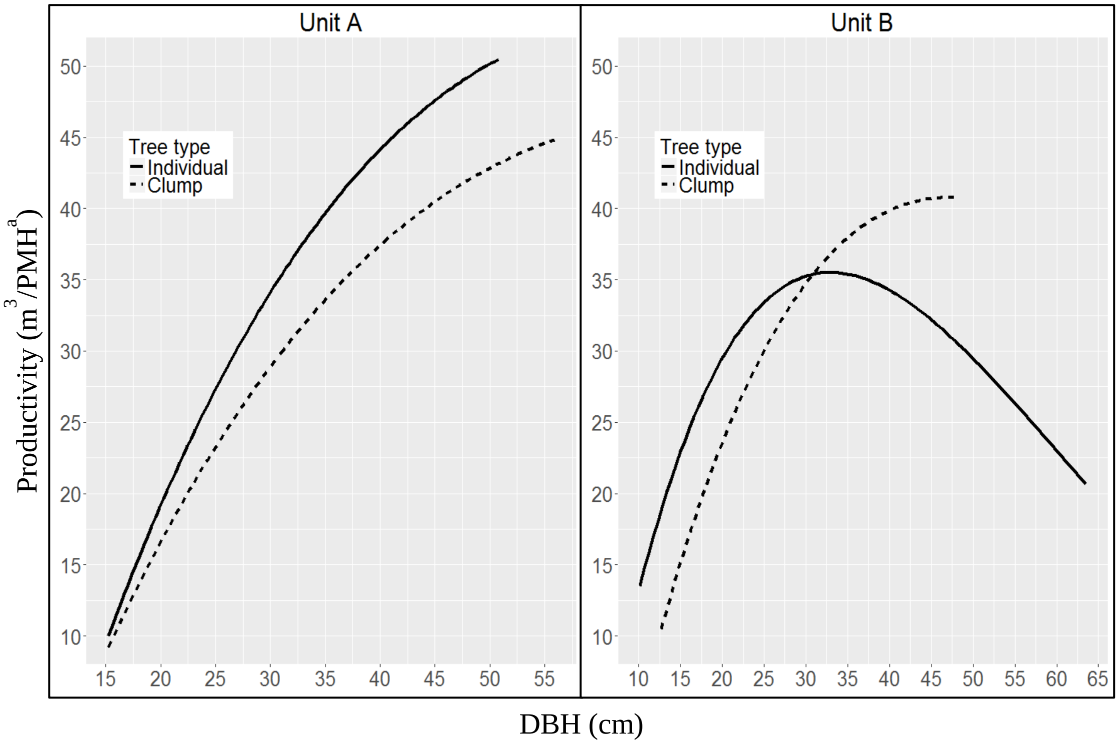


[a]productive machine hour.

Figure 2. Predicted thinning productivity (m^3/PMH) of the harvester relate to tree size in DBH (cm) and move distance (m) between harvested trees in redwood forest.

Distance between harvested trees was also an important factor that influenced the productivity of felling and processing operations (Ghaffariyan et al. 2013). The relationship between distance and productivity was based on the time study data for harvesters (**Figure 2**). These results indicate that time consumption for moving decreased when the initial stand was dense and the number of harvested trees increased (Tufts 1997). Due to the fact that an average of six stems were gathered in the old stump, the harvester usually felled and processed trees without moving any distance which resulted in a low average move distance.

The specific characteristics of redwood, which formed a clump from the old stump, also affected DFC time and the productivity of the harvesters. For positioning and felling the clump stands, the harvester heads generally consumed 1.2 and 2.4 seconds more than those of individual stands. The main reason was due to the fact that stems from the same stump were gathered close. This resulted in a lack of space for the harvest head to get into position. The operators usually spent time for penetrating inside and re-positioning head when felling clump stands. This increased the total time results in lower productivity than individual stands (**Figure 3**). However, in Unit B, the productivity of processing individual stands decreases when tree size is over 30 cm DBH and also lower than clump stands. This difference can be explained by the different machine sizes and operator skill. Individual stands, such as Sitka spruce and Douglas fir, have more thick and dense branches than redwood has. As the tree size increases, the size of branches in individual trees increases. Due to these branches in individual stands, the harvester head rolled over the stem several times to remove these branches, which increased the total DFC time. These result indicated that the denser the number of stems and the larger stem size and more composition of clump stands, the lower the average productivity of the harvester.



[a]productive machine hour.

Figure 3. Predicted thinning productivity (m^3/PMH) of the harvester relate to tree size in DBH (cm) and tree type in individual and clump tree in redwood forest.

The number of logs produced from each stem was the only factor that influenced productivity of the harvester in Unit B. These results can be explained by the operator's skill and experience. Human factors such as operator skill could affect productivity (Purfürst and Erler 2011). The harvester operator took time to decide how many logs top produce per stem. This study did not conduct a human factor, thus future research should include this factor.

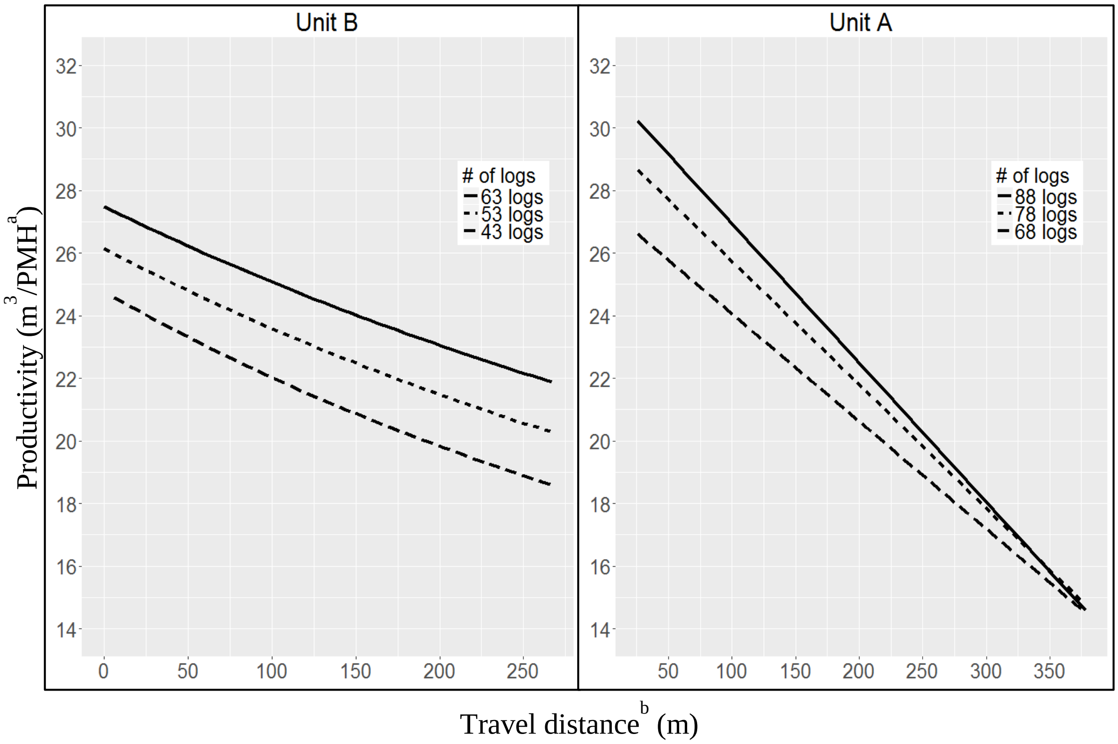
Processing of tree-top and brushing are important factors in determining productivity of felling and processing operations even though, brushing time could not have a relationship with measured stand information (Spinelli et al. 2002). To reduce soil disturbance, the CTL system usually generates residual limbs, foliage, and tree-top and put those over the operating trail while processing trees in harvester operation (Labelle and Jaeger 2011). Processing of tree-tops and brushing accounted for 33% of DFC time with an average of 19.3 seconds in Unit A, while, 27% of DFC time with 16.3 seconds was processing of top and brushing in Unit B. This difference can be explained by the need to generate more slash on the trail during winter operations. Because the purpose was to reduce the vertical continuity of vegetative fuels and the horizontal continuity of tree crowns in Unit A, the harvester concentrated more time for processing of tree-top and brushing on the ground than the harvester used in Unit B.

The productivity of felling and processing operations in this study was comparable to the mean productivity in previous studies. The productivity in this study was 28.8 and 35.6 m^3/PMH for average log volume with 0.46 and 0.59 m^3 per stem for each unit, respectively. Apăfăian et al. (2017) observed 26.5 m^3/PMH for 0.36 m^3 per stem in a Norway spruce clear-cutting. Tufts (1997) studied Ponsse HS-15 harvester and observed 34.6 m^3/PMH for stem volume from 0.04 to 0.59 m^3 in pine stands at central Alabama. Kellogg and Bettinger (1994) observed in a range of 30.3 to 34.4 m^3/PMH for stem volume of 0.41 and 0.51 m^3 per tree. The productivity of this study was higher than the productivity of a harvester in hardwood forests. Li et al. (2006) found 9.2 m^3/PMH for trees with 0.42 m^3 stem volume. A productivity of 14.0 m^3/PMH for 0.20 m^3 per stem was reported by Suchomel et al. (2011) in oak stands. LeDoux and Huyler (2001) also found in a range of 11.1 to 14.8 m^3/PMH for the average of 0.16 m^3 and 0.31 m^3 per tree volume in mixed hardwood and softwood stands. However, Ghaffariyan et al. (2013)

observed that the productivity of the harvester was 56.7 m^3/h. This difference can be explained by their large average tree size of 68 cm DBH.

Forwarding operations

The productivity of the forwarders was significantly affected by the number of logs per load and travel distance in this study, and similar to previous study (Wang et al. 2005; Adebayo et al. 2007). The productivity increased with more number of logs per turn and shorter travel distance (**Figure 4**). The number of logs were positively related to the productivity, whereas, travel distance negatively correlated.



[a]productive machine hour.

[b]travel loading distance at Unit A; travel full distance at Unit B.

Figure 4. Predicted thinning productivity (m^3/PMH) of the forwarder relate to travel distance (m) and number of logs in redwood forest.

The productivity of forwarding operations was in a range of 22.4 to 23.3 m^3/PMH for the average volume of 0.26 m^3 per log. The productivity of this study was comparable to the productivity of forwarder in previous studies. Wang et al. (2005) found in a range of 20.0 to 29.0 m^3/PMH for hardwood stands. In thinning of conifer stands, a productivity of 10.2 to 14.5 m^3/PMH was observed by Kellogg and Bettinger (1994) for 5.4 m sawlogs and 6.1 m pulpwood.

The harvester in this study could process 28% more volume than the forwarder could forward to the landing. This allowed the harvester to work comfortably ahead of the forwarder, increasing the space between working areas and, therefore, increased the operating safety and creating a productivity efficiency.

Stump-to-truck costs

The stump-to-truck cost for Unit A was slightly higher (\$5.70/m^3) than the cost at Unit B. This difference can be explained by differences in machine costs for each harvester and productivities of each machine. Due to the fact that bigger machines have higher purchase price and all associated costs, the harvesting costs are increasing with larger machines under similar stand conditions. The hourly machine cost for harvester (\$229.50/PMH) in Unit B was less than the cost of a harvester (\$290.80/PMH) at Unit A because the purchase price for Unit B harvester was about 26% less than those price for Unit A harvester.

The stump-to-truck costs of this study were comparable to the costs of previous. Adebayo et al. (2007) found the stump-to-truck costs in a range from \$11.70 to

\$12.50/m^3. This difference was due to the fact that its average productivity was higher than the one found in this paper. Kellogg and Bettinger (1994) observed the stump-to-landing cost of \$12.50/m^3 which is lower than the one found in this paper (ranged from \$15.20 to \$19.30/m^3). This difference can be explained by its lower machine cost for each machine, even though the average productivities of this paper was similar or higher than those in their paper.

This research has proved just like the studies of other authors that stem size and travel distance affect the productivity of the harvester and forwarder (Kellogg and Bettinger 1994; Li et al. 2006; Adebayo et al. 2007). The results of this study confirmed the hypotheses that thinning clump trees have significant influences on the productivity in the young third-growth redwood plantations.

CONCLUSIONS

This study evaluated thinning productivity and costs of CTL harvesting systems which has been introducing for the first time in redwood forests in northern California. Historically, this system was not used in logging operations in this regions because the size of the redwoods was too large to be harvested. The study results indicated that this system could be an effective thinning tools in young third-growth redwoods and in summer and winter seasons. Thinning productivity and costs of CTL systems are affected by stand and harvesting variables. The harvester productivity and cost are influenced by tree size (DBH), distance, number of logs per stem, clump, and number of top processing. The productivity and cost of forwarders depend on the travel distance and number of logs per turn. Reducing the operational delays by applying an appropriate plan would improve the productivity and lower the thinning costs of each machine.

Future research is needed to include the effect of other factors not investigated in this study. Using an individual loader for loading logs onto the truck was less productive than using a forwarder without loader (Adebayo et al. 2007). Because this was not part of study, future research can compare the effect of machine combination which includes individual loader on cost and productivity of CTL harvesting. Also effect of fuel reduction harvesting should be included in future study.

It is anticipated that land managers can refer to the results of this study to predict productivity and costs for the CTL harvesting system in similar stand conditions in northern California. Furthermore, this study provides logging contractors with detailed information on equipment productivity and thinning costs with the CTL system.

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APPENDIX A

Appendix A: Summary of average harvester cycle elements and independent variables that were collected in individual stand and clump stand in Unit A redwood forest.

	Individual stand[a]		Clump stand[b]		
Cycle elements	Average time (seconds)	Percent (%)	Average time (seconds)	Percent (%)	p-value[c]
Move	6.8 (8.7)[d]	12.1	4.5 (8.2)	7.8	0.0004
Fell	13.8 (4.7)	24.7	19.1 (7.8)	32.6	< 0.0001
Process	15.2 (10.4)	27.3	15.8 (10.1)	27.0	0.4399
Top	5.8 (2.6)	10.5	5.8 (2.5)	9.9	0.8986
Brush	14.2 (23.2)	25.4	13.3 (20.8)	22.7	0.5914
Delays	6.5 (25.1)	-	9.8(26.1)	-	0.0478
Average DFC	55.8 (29.5)	100	58.5 (27.0)	100	0.1999
Independent variables	Average	Range	Average	Range	
Distance (m)	2.5 (4.9)	0 – 64	1.7 (3.4)	0 – 61	0.5864
DBH[e] (cm)	24.0 (7.0)	15 – 51	24.7 (7.2)	15 – 56	0.1533
# of logs	1.5 (0.5)	1 – 3	1.7 (0.6)	1 – 3	0.0003
# of cuts	1.9 (1.1)	0 – 5	2.2 (1.2)	0 – 6	0.0300

[a] sample size = 246 trees.
[b] sample size = 886 trees.
[c] two-sample t-test ($\alpha=0.05$) between individual trees and clump trees.
[d] values in ( ) indicate standard deviation.
[e] diameter at breast height.

APPENDIX B

Appendix B: Summary of average harvester cycle elements and independent variables that were collected in individual stand and clump stand in Unit B redwood forest.

	Individual stand[a]		Clump stand[b]		
Cycle elements	Average time (seconds)	Percent (%)	Average time (seconds)	Percent (%)	p-value[c]
Move	4.3 (11.1)[d]	7.5	3.6 (11.7)	5.9	0.1949
Fell	14.8 (6.9)	25.6	18.5 (8.5)	30.6	< 0.0001
Process	20.7 (25.0)	35.8	23.3 (21.3)	38.6	0.0301
Top	5.2 (2.9)	9.0	4.9 (2.6)	8.2	0.0796
Brush	12.7 (23.0)	22.1	10.1 (20.4)	16.7	0.0198
Delays	8.6 (37.4)	-	9.5 (42.0)	-	0.6755
Average DFC	57.7 (40.6)	100	60.4 (33.5)	100	0.1666
Independent variables	Average	Range	Average	Range	p-value
Distance (m)	1.7 (5.4)	0 – 74	1.3 (6.6)	0 – 156	0.2870
DBH[e] (cm)	23.1 (7.4)	10 – 64	24.9 (6.5)	13 – 48	< 0.0001
# of logs	2.0 (0.8)	1 – 4	1.8 (0.7)	1 – 5	0.0008
# of cuts	1.5 (0.9)	0 – 6	1.5 (1.0)	0 – 5	0.2094

[a] sample size = 688 trees.

[b] sample size = 798 trees.

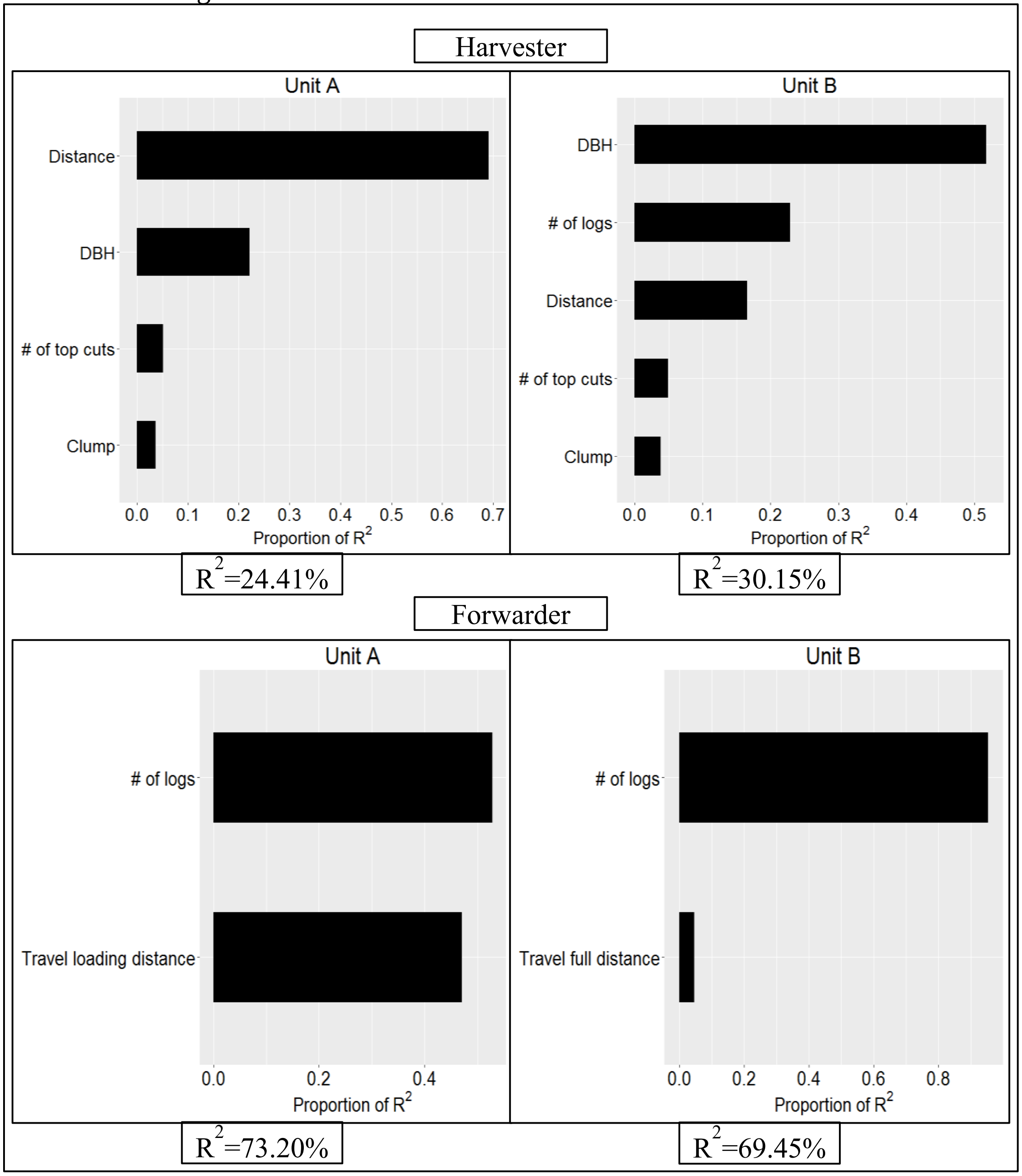
[c] two-sample t-test (α=0.05) between individual trees and clump trees.

[d] values in ( ) indicate standard deviation.

[e] diameter at breast height.

APPENDIX C

Appendix C: Relative importance to the total cycle time for each of variables that are included in the regression models for harvester and forwarder.



APPENDIX D

Appendix D: Goodness of fit in terms of Akaike's Information Criterion for small samples(AICc), square root of the mean squared error (RMSE), and the adjusted R^2 (R^2 adj.) of linear models predicting loading (forwarder) delay-free cycle time in Unit B. The global model included dummy variables for move versus stay (Move), number of logs to truck (Logs to truck), and number of logs from deck to bunk (Logs to truck). n = 15 cycles.

Unit B loader (forwarder) (DFC[a])$^{-1.5}$=	AIC_c	ΔAIC_c[b]	RMSE	$R^2_{adj.}$
(1.460E-05) - (7.268E-07 * Move[c]) - (6.005E-08 * Logs to truck) - (1.521E-09 * Logs to bunk)	-350.50	3.20	1.4620E-06	0.0301
(1.315E-05) - (4.845E-08 * Logs to truck) - (1.317E-08 * Logs to bunk)	-351.85	1.85	1.4943E-06	0.0711
- (1.089E-06)	-352.43	1.27	1.6747E-06	0.0000
(1.465E-05) - (7.416E-07 * Move) - (6.054E-08 * Logs to truck)	-352.50	1.20	1.4621E-06	0.1108
(1.332E-05) - (5.108E-08 * Logs to truck)	-353.70	0	1.5019E-06	0.1338

[a] delay-free cycle time (centi-minutes).

[b] ΔAIC_c = decrease in AIC_c from the best model in terms of AIC_c.

[c] 1 if move; otherwise 0.