# Productivity and Cost of a Cut-To-Length commercial thinning operation in a Northern California Redwood Forest

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**Abstract**

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 from stems that sprout from stumps after a harvest. This can be a challenge without damaging residual trees which can decrease productivity and increase costs. This study evaluated the productivity and cost of a CTL thinning operation performed in a redwood forest. Standard time and motion study methods were used to calculate the productivity of a harvester and forwarder used during the rainy, winter months. Key factors that influenced productivity for the machines, such as tree diameter and forwarding distance, were evaluated. To comply with prescription requirements, the forwarder spread slash so that it did not exceed a height of 46 cm throughout the harvest unit. This study produced productivity and cost estimates for the harvesting at 27.7 $m^3$ per productive machine hour (PMH) at a cost of $8.30/ $m^3$, forwarding at 22.4 $m^3$/PMH and $8.20/ $m^3$, and loading at 58.9 $m^3$/PMH and $3.10/ $m^3$, respectively. Increased requirements for soil protection and fuel treatments in winter operations caused high thinning costs in redwood forests.

**Keywords:** forest operation, detailed time study, thinning productivity, harvester, forwarder, stump-to-truck

## Introduction

Mechanized harvesting systems produce consistent and high-quality end-products, require small crew sizes, and create a safer work environment compared to manual harvesting systems (Kellogg and Bettinger, 1994). The amount of mechanization and complexity of machines and systems in harvesting operations keeps increasing in spite of rising owning and operating costs (Brinker et al. 2002). Cut-to-length (CTL) harvesting system are a good example of this. They have several differences from conventional methods which consist of a feller-buncher, skidder, loader, and processor. The felling, delimbing, and bucking occur at the stump, and the lengths of the end-product are typically shorter (Bettinger and Kellogg, 1993).

A harvester and forwarder are the two machines used in a CTL system. The harvester fells, processes (delimbs and buck) stems at the stump. When delimbing, limbs and tops are placed in the skid trail to form a mat for equipment travel. The retention of branches and foliage also retains nutrients and organic matter on site and reduces the potential for adverse soil impacts (Hartsough et al. 1997). The forwarder transports the processed logs to the roadside or landing site (Kellogg and Bettinger. 1994). The greatest disadvantages of these systems are the high investment cost of the harvester and processor head. These systems can have a maintenance costs

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due to the machine's complex, computerized electrical system. They are further limited by their inability to handle stems larger than 56 cm in stump diameter (LeDoux and Huyler. 2001). The purpose of this study is to evaluate the productivity and cost of a harvester and forwarder in a CTL commercial thinning operation in a redwood stand. The literature on productivity and costs has been dominated by a focus on the other species such as Douglas-fir and harvesting systems (Adebayo et al., 2007; Tufts, R.A., 1997; Hartsough et al., 1997). No attempt has been made to study CTL systems in redwoods, especially those growing in clumps. Evaluation of the productivity and costs of the new harvesting system will be important to redwood country land managers.

## Methods

### Study site description

The study site was located on commercial timberlands in northern California that were clear-cut during the mid-1990. The thinning area was 10.1 Inventory data before and after harvest was collected from 25, 1/25-hectare plots within the harvest unit. The unit was characterized as third-growth redwood (*Sequoia sempervirens*) stand which naturally sprouted from stumps from the previous even-aged harvest. The dominant species was redwood with natural regeneration of red alder (*Alnus rubra*), planted Douglas fir (*Pseudotsuga menziesii*) and Sitka spruce (*Picea sitchensis*). At any season of the year, redwoods can sprout in clumps from stumps (Show. 1932). Because of this trait, many of the redwoods in the unit were in multiple stem clumps on old stumps.

Table 1. Pre- and post-thinning descriptions of stand characteristics used for the study

| Characteristics | Pre-thinning | Post-thinning |
|---|---|---|
| Average DBH[a] (cm) | 20 | 23 |
| Average height (m) | 20 | 19 |
| Average # of clump (# stems/clump) | 6 | 3 |
| Average basal area ($m^2$/ha) | 99 | 40 |
| Trees per hectare | 2393 | 769 |
| Species composition (%) | | |
| redwood | 77 (1850)[b] | 79 (606) |
| red alder | 17 (394) | 15 (113) |
| Douglas-fir | 5 (114) | 4 (34) |
| Sitka spruce | 1 (14) | 2 (17) |

[a]diameter at breast height
[b]trees per hectare

### Harvesting systems and operations

The system included a single grip harvester (Ponsse Bear H8) that felled, delimbed, and bucked trees prior to forwarding them with a forwarder (Ponsse Buffalo 8w). When the harvester generated its trails, the forwarder followed that trail for forwarding logs. The operation gap between harvester and forwarder was two to three days because it provided sufficient logs for the forwarder. The harvester operator selected the trees for removal based on his judgment, removing the smaller and poorer-quality trees. The harvester produced 1.8, 3.7, 5.5, and 7.3 meter length logs for each tree. The minimum small end diameter that the harvester produced was 15 cm. Stems less than 15 cm diameter were used to generate a slash mat to reduce soil compaction. In this study, the forwarder was also used as a loader at the landing to load piled logs onto the trucks. The harvester and forwarder cycle was divided into small elements and delays (Table 2.)

Table 2. Harvesting elements, delays and their descriptions

| **Element** | **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 trees has been completely processed. |
| Top bucking | Starts when the head bucks the top and ends when the operator is ready to begin the next task. |
| Brushing | Starts when head cuts and processes the trees top and 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. |

**Data analysis**

A detailed time study was conducted to measure the harvesting cycle data, small delays, and production rates. Prior to harvest operation, 300 pre-marked trees were measured. Tree species, DBH, height, and clump number were collected to estimate the harvester productivity. One person rode in the harvester cab and recorded the cycle time, DBH, existence of clump, and length of each piece cut (displayed on cab console). The Shapiro-normality test and Kruskal-Wallis test were used to compare the time consumption between clump trees and individual trees. Each machine's length was used to estimate the distance travelled within the unit. Forwarder data was collected by one person. Before forwarder operations started, log lengths, large end diameter, and small end diameter were recorded from as many pieces possible. Multiple linear regression analysis was used to develop models for predicting productivity of the harvesting operation.

Hourly machine costs were estimated using standard machine rate calculation methods from Brinker et al. (2002). Initial machine prices were based on the project contractor and dealers. Estimated economic life for all machines was set at five years with 2,000 working hours per year. Diesel prices were determined from the local market prices in effect during the study. Salvage value was set at 20 percent of the initial machine price. Interest was set at 8 percent, insurance at 4 percent, and taxes at 2 percent of initial machine price. At 36.8 percent lubrication cost was estimated based on fuel cost. Labor costs were determined by personal communication with an individual operator.

## Results and Discussion

### Harvester productivity

The study site had a pre-harvest average of 2393 trees per hectare, and approximately 70 percent of total trees were cut. The harvester felled, processed, and top bucked one tree at a time into delimbed and bucked merchantable logs. The total average time to move, fell, process, top buck, and brush was 60 seconds. A total of 773 trees were used to estimate the productivity of the harvester. The number of logs manufactured per cycle ranged from 1 to 3, with an average of 1.6 logs per tree. A majority of the total cycle time (67%) was consumed by felling, processing, and top bucking.

The productivity of the harvester generally depended on the size of the tree, such as DBH (Hånell et al. 2000; Yaoxiang et al. 2006; and Adebayo et al. 2007). As tree size increased, the productivity and cost of the harvester changed (Figure 1). However, the productivity did not linearly increase over 30 cm DBH. The log volume increased as tree size increased, but the increased cycle time can offset the increase. The harvester took more time to handle large trees because of their size and weight.

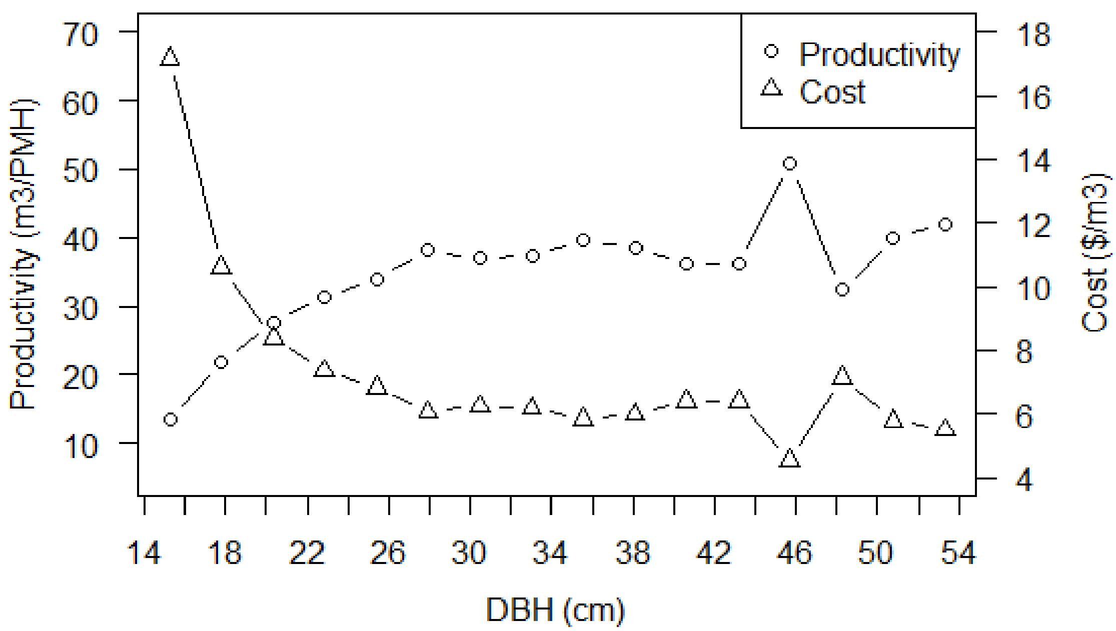


Figure 1. Predicted productivity ($m^3$/PMH) and cost ($/$m^3$) of the harvester relate with tree size in DBH (cm)

The number of harvested trees and the harvesting prescription affected machine movement and brushing. The move element occurred infrequently with average move distance of 4.6 m per cycle. This suggests that dense stands decrease move times. The second most time-consuming cycle element was brushing, which averaged 30 seconds. These results were higher than a previous study (Kellogg and Bettinger, 1994). This implies that reducing the brushing time makes harvesters more productive.

Most of the delays were operational at 93 percent. These delays were typically caused from trees getting hung-up during felling, arranging slash in the trail, and clearing uncut stumps. Because of heavy stand density, tree hang-ups occurred frequently. A small portion of the delay time was personal at 5 percent, such as personal communication. Mechanical delay at 2 percent consisted of chain replacement.

Redwood clumps took more time to cut than individual trees ($p < 0.05$). However, clumps reduced the amount of time the harvester needed to move to the next tree. The harvester sometimes would “pluck” or partially cut and pull a tree from the clump. By plucking, the harvester could open up the clump and fell nearby tree more efficiently without damaging residual trees. However, further study will be required to estimate the damage to residual trees from clump harvesting.

The regression equation of the time elements and volumes on production per PMH was created to predict harvesting cycle time (Table 4). In this equation, move and brushing were added as constants.

**Forwarder productivity**

The forwarding elements included travel empty, load, travel loading, arrangement, travel full, and bunk to deck. The forwarder productivity averaged 22.4 $m^3$ per PMH. The average time for forwarding cycle was 55.4 minutes with an average number of logs per bunk load of 78. The forwarder productivity was affected by product type, payload volume, and forwarding distance (Kellogg and Spong, 2004; Yaoxiang et al., 2006). The most time-consuming elements were loading and unloading. These elements accounted for 64 percent of the total delay-free-cycle with an average of 35 minutes. As loading volume per grapple swing increased, loading and unloading time per log volume decreased. The average travel empty time was 2.7 minutes with an average distance of 96.4 m. Average travel loaded cycle time was 6.5 minutes, with an average distance of 133.6 m. Travel full cycle time averaged 2.5 minutes with a distance of 88.2 m.

Most of the delays were from personal at 51 percent, and were primarily personal communication. Operational delay time consisted of brushing time and accounted for 45 percent of total delay time.

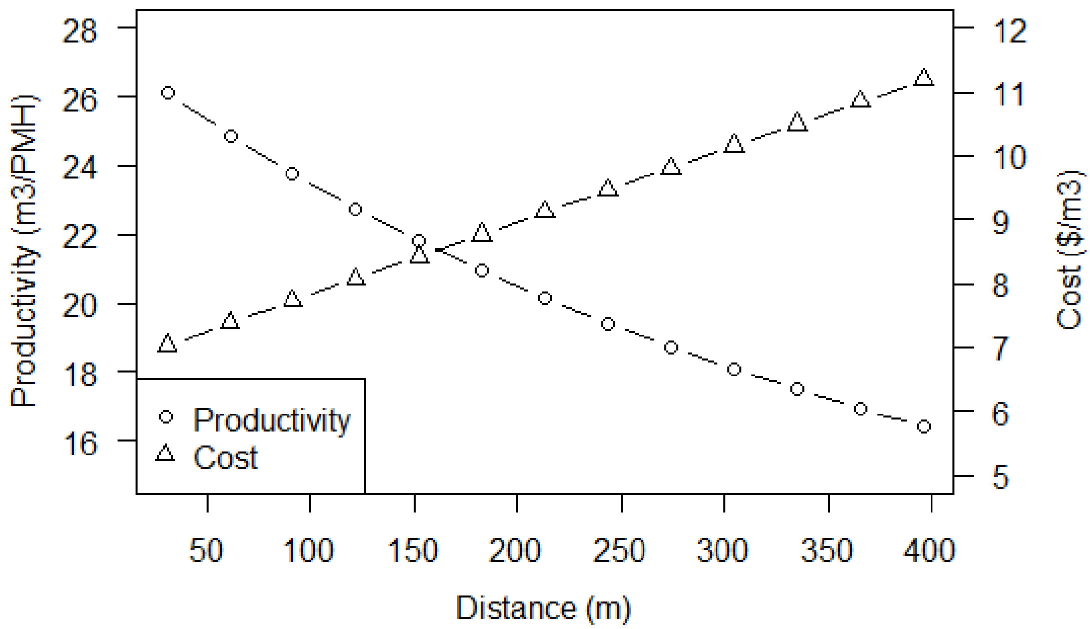


Figure 2. Predicted productivity (m3/PMH[a]) and cost ($/m$^3$) of the forwarder relate with loaded moving distance (m)

**Harvesting cost**
The capital cost of the harvester and forwarder were approximately US$650,000 and $490,000, respectively. The estimated cost of operating a harvester is $230.9/ PMH while the cost of operating a forwarder is $183.6/PMH. The initial price and other ownership costs of a harvester were about 20 percent higher than those costs for a forwarder. This difference makes harvester has highest harvesting cost even though harvester has high hourly production than the production of forwarder. On the average, the harvester, forwarder, loader produced 27.7 m$^3$/PMH, 22.4 m$^3$/PMH, and 58.9 m$^3$/PMH, respectively. The stump-to-truck cost for this study was $19.7/m$^3$ (Table 3). This cost was about 40 percent more expensive compared to previous studies (Adebayo et al., 2007; Kellogg and Bettinger, 1994). In this study, the stump-to-truck cost excluded move-in/out and support vehicle costs, overhead, and profit-and-risk allowance.

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

| | Machine cost ($/PMH[a]) | Hourly production (m$^3$/PMH) | Harvesting cost ($/m$^3$)[b] | Percent of total cost (%) |
|---|---|---|---|---|
| Harvester | 230.9 | 27.7 | 8.3 | 42.4 |
| Forwarder | 183.6 | 22.4 | 8.2 | 41.7 |
| Loader (Forwarder) | 183.6 | 58.9 | 3.1 | 15.9 |
| Total | 598.1 | | 19.7 | 100 |

[a]productive machine hour
[b]these costs do not include move in/out cost, overhead, profit-and-risk allowance

Table 4. Delay-free average cycle time for a cut-to-length harvesting machines

| Machines | Average cycle time estimator (centi-minutes) | $r^2$ | p-value |
|---|---|---|---|
| Harvester | (MV+BS+3.6646)+2.3543SP+1.2699DBH+9.7517Clump+7.4507TS+5.4396FF+10.2765ST+4.8887Cuts | 0.29 | 0.0001 |
| Forwarder | (-1260.7275)-1.5391EDIST+7.6626LDIST+0.9402FDIST+74.8245PIECE | 0.75 | 0.0001 |
| Loader (forwarder) | (751.1028)+0.9074DIST+27.4854DTTLOG+11.9293DTBLOG-1.9215BTTLOG | 0.95 | 0.0001 |

**MV**-move time,
**BS**-brushing
**SP**-“1” if it was redwood “2” if it was red alder “3” if it was Douglas fir “4” if it was Sitka spruce ($p > 0.05$)
**DBH**-diameter at breast height ($p < 0.05$)
**Clump**-“1” if it was clump “0” otherwise ($p < 0.05$
**TS**-log length 3.7m ($p <0.05$)
**FF**-log length 5.5m ($p < 0.05$)
**ST**-log length 7.3m ($p < 0.05$)
**Cuts**-number of cuts ($p < 0.05$)
**EDIST**-empty moving distance ($p > 0.05$)
**LDIST**-loaded moving distance ($p < 0.05$)
**FDIST**-fully loaded moving distance ($p > 0.05$)
**PIECE**-number of piece loaded and unloaded ($p < 0.05$)
**DIST**-moving distance ($p >0.05$)
**DTTLOG**-number of logs that loaded from deck to truck ($p > 0.05$)
**DTBLOG**-number of logs that loaded from deck to bunk ($p < 0.05$)
**BTTLOG**-number of logs that loaded from bunk to truck ($p > 0.05$)

**Conclusion**

Cut-to-length operations are being applied for thinning in the Northern California for the first time. Redwood clumps can be a challenge for harvester operators when selectively cutting trees in the redwood forest. Regression equations were developed for redwood forest to predict delay-free cycle time of cut-to-length machines. In similar stands, the delay-free cycle time of forwarder and loader may be predicted with developed equations, while there are limitations in predicting harvester delay-free average cycle time with the equation. Cut-to-length harvesting productivity and cost are affected by stand and other harvesting variables. Harvesting cost can be changed in cut-to-length harvesting by applying different silvicultural treatment.

High brushing cycle time, which accounted for 23 percent of the total delay-free cycle was caused by a management requirement for winter operation to reduce soil compaction. Delimbed branches and tops were also left on the ground to protect against soil compaction and reduce fuel. This can be a solution for the problem of soil compaction, but further study is required to compare the effects of other variables not considered in this study, such as different harvesting prescription and operator skill.

The result of this study can be referred by landowners to use appropriate machine combinations on their property. Also, this study produced information that can be used by logging contractors to increase productivity and reduce thinning costs with the cut to length harvesting system.

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