Effect of Tree Size on Productivity and Time Required for Work Elements in Selective Thinning by a Harvester

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ABSTRACT

The effect of diameter at breast height (DBH) on the time required for work elements in felling, delimbing, and bunching by a harvester was studied. Move and boom, position, felling and tree fall, and cross cutting were not affected by the DBH of the harvested tree. On the other hand, the greater the DBH of the harvested tree, the significantly longer the time required to delimb because of increasing tree height and decreasing delimbing speed. Nonetheless, the total time required to fell, delimb, and bunch one tree was not affected by its DBH, because the proportion of time for delimbing was only 16 percent of the total time. As a result, the productivity of the harvester was 9.2 m^3 per productive machine hour, about 33.4 times the piece volume of the harvested tree. This study demonstrated that harvester productivity varied in a roughly linear manner with the piece volume of the harvested tree in a single tree selective thinning that removed only a small percentage of the stand volume.

Keywords: *harvester, felling, delimbing, bunching, work element, excavator, DBH, piece volume, Japan, Larix*

Introduction

In Japan, many planted forests were established in 1950s, 1960s, and 1970s. Thus, most of the planted forests now need to be thinned. Forestry in Japan, however, has become economically unprofitable because of weak timber prices and the increasing cost of reforestation and forestry worker wages. In addition, government subsidies for forestry are being significantly reduced because of fiscal reconstruction. On the other hand, forestry can provide carbon benefits at some spatial and temporal scales, a renewable resource, and also employment in rural areas.

Thus, it is necessary to lower the cost of timber harvesting to make forestry a profitable industry. One of the ways to accomplish this is mechanization of forestry works. For instance, powerful forestry machines, such as harvesters, can significantly increase the productivity of harvesting trees.

A harvesting operation consists of several work elements, such as moving from tree to tree, booming, positioning, felling, tree fall, delimbing, crosscutting, and bunching. An analysis of each work element could lead to improvements in harvesting operations. Although such analyses in selective thinning in even-aged stands are very useful to forestry mechanization in Japan, most studies on work elements of harvesters were done in Scandinavia and North America for clearcutting and shelterwood cutting (Eliasson 1999, Eliasson and Lageson 1999, Hartsough and Cooper 1999, Eliasson 2000, Hånell et al. 2000). The time required for harvester work elements in selective thinning in even-aged stands could be different from those in clearcutting or shelterwood cutting. In this paper, the effect of diameter at breast height (DBH) on the time required for specific work elements in felling, delimbing, and bunching in selective thinning by a harvester and its possible application for prediction of harvester productivity in even-aged stands are reported.

Study Site

The study was conducted in compartment 67, sub-compartment 103 of the privately owned stand in Otofuke-cho, Hokkaido, the northernmost island of Japan. **Table 1** provides information on the study site. Thinning was to be carried out at this stand, and marking of trees to be harvested had been done by Otofuke-cho Forest Owners' Association before this study was planned. Thinning from below was not necessarily intended, but as the result of selecting trees with undesirable characteristics or with less vigor, smaller trees were removed (**Fig. 1**).

Materials and Methods

A rectangular plot, 68.7 m by 67.0 m (0.46 ha), was established within the stand. DBH and height of all trees to be harvested and several trees to be left within this plot was measured. Whether a tree was marked for harvesting or not was also recorded. All of the trees in the plot were numbered

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Table 1. ~ *Information on the study site.*

Slope degree	18°
Slope aspect	Northeast
Species planted	*Larix kaempferi*
Age of the stand	27 years
Density of planted trees	481/ha
Distance between standing trees	4.6 m
Volume of planted trees	185.70 m^3/ha
Average DBH of planted trees	23.0 cm
Number of trees to be thinned	100/ha
Distance between harvested trees	10.0 m
Percentage of trees to be thinned	20.8%
Volume of trees to be thinned	27.54 m^3/ha
Average DBH of trees to be thinned	20.0 cm
Density of hardwood (> 16 cm)	30/ha
Volume of hardwood (> 16 cm)	2.68 m^3/ha
Average DBH of hardwood (> 16 cm)	18.7 cm

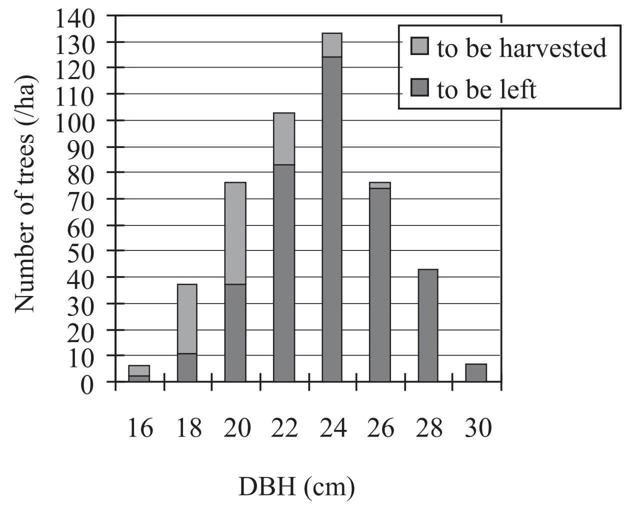

Figure 1. ~ *DBH distribution of trees to be harvested and to be left in the study plot.*

with a numbering tape and a red color spray. In the plot, 46 trees were to be harvested.

Sawing a standing tree, felling, delimbing, and bunching was carried out by an excavator-based harvester (Tamaoki TM-35s attached on Caterpillar 307B) on September 28, 2004. **Table 2** shows the technical data of the harvester, and **Table 3** shows those of the base machine used in this study. The harvester head was designed to be attached on an excavator.

Whole stems were yarded by crawler-type skidders equipped with winches. Bucking was carried out using chain saws at the landing. Diameter of the top ends and lengths of processed timber for the 46 trees were measured immediately after processing, and the timber volume was calculated based on them.

The harvesting operation was recorded with a video camera. At the same time, the assigned number of a tree being harvested was voiced so as to be recorded with the video. Productivity analyses for yarding and bucking are excluded from this paper.

By viewing the videotapes, the time required for specific work elements was recorded in a laboratory. Work elements analyzed in the present study are:

- move and boom (movement of crawlers, swinging of the excavator, and boom to the next tree),
- position (grabbing a tree by a harvester head),
- felling and tree fall (sewing standing tree and making tree stem horizontal),
- delimbing, and
- cross cutting (cutting a butt end and a tree top).

Cutting a butt end is necessary when the butt end of a stem is not straight, which is common for plantation of *Larix kaempferi* in Hokkaido. Bunching was not necessary for the first tree stem in each bundle of stems or in cases where the stem position happened to be just above the stem bundle after delimbing.

Effects of DBH on the time required for specific work elements and the total time for one tree were analyzed by simple linear regression analyses. The effect of tree height on the time required for delimbing, the effect of DBH on delimbing speed, and the effect of piece volume of the harvested tree on harvester productivity were also analyzed by simple linear re-

Table 2. ~ *Technical data of the harvester head, Tamaoki TM-35s.*

Maximum sawing diameter	400 mm
Maximum delimbing diameter	350 mm
Minimum delimbing diameter	20 mm
Rotating angle	300°
Delimbing device	1 fixed + 2 moving knives
Feeding device	Rubber rollers with chains
Diameter of feeding roller	380 mm
Feeding speed	2.0 m/sec.
Chainsaw pitches	0.404 in.
Length	1140 mm
Width	1200 mm
Height	2080 mm
Weight	750 kg
Hydraulic pressure	22556 kPa
Hydraulic flow	100 (l/min.)
Suitable excavator (bucket capacity m^3)	0.28 to 0.50

Table 3. ~ *Technical data of the excavator, Caterpillar 307B.*

Weight	6550 kg
Bucket capacity	0.28 m^3
Swing speed	11.0 $min.^{-1}$
Maximum slope to crawl	35°
Ground pressure	30.4 kPa
Transport length	6.08 m
Transport height	2.64 m
Transport width	2.28 m
Ground clearance	0.355 m
Rear radius of swinging	1.75 m
Engine power	41 kw
Engine rotation	2100 $min.^{-1}$
Relief valve pressure	27500 kPa

Table 4. ~ *Results of simple linear regression analyses of the time for specific work elements and the total time for one tree on the DBH of the harvested tree.*

Dependent variable	Y intercept	Regression coefficient	p for regression coefficient	r^2
Time for move and boom	28.64	0.5952	> 0.25	0.0018
Time for position	3.84	0.0092	> 0.25	0.0001
Time for felling and tree fall	12.83	–0.1251	> 0.25	0.0029
Time for cross cutting	2.45	0.2435	> 0.25	0.0175
Total time for one tree	111.80	–0.1895	> 0.25	0.0043

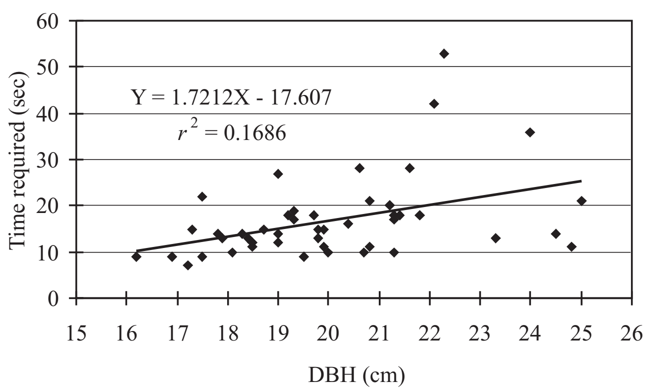

Figure 2. ~ *Simple linear regression analysis of the time for delimbing on the DBH of the harvested tree.*

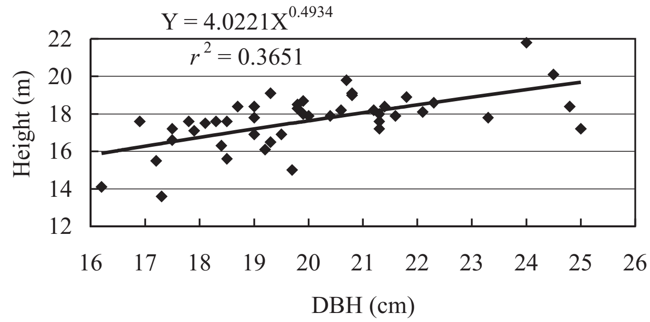

Figure 3. ~ *The relationship between DBH and height of the harvested trees.*

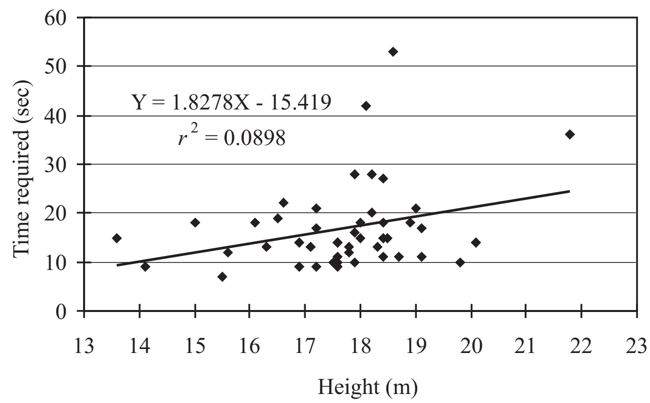

Figure 4. ~ *Simple linear regression analysis of the time required for delimbing on the height of the harvested tree.*

gression analyses. Relationships between DBH and tree height and DBH and piece volume were analyzed by simple linear correlations after log transformations of data. The level of significance, α, was set at 5 percent for all of the statistical analyses.

Results and Discussion

Table 4 and **Figure 2** show the results of regression analyses of time for specific work elements and the total time for one tree on DBH of the harvested tree. Only delimbing was affected by the DBH of the harvested tree; the greater the DBH of the harvested tree, the significantly longer the time for delimbing ($0.0025 < p < 0.005$) (**Fig. 2**).

The effect of tree size on the time required for each work element differs depending on reports. Work elements found to be affected by either DBH or piece volume of the harvested tree were:

- delimbing (Fukazawa and Tamayama 1998);
- processing (delimbing and cross cutting) (Tufts and Brinker 1993, Suadicani and Fjeld 2001);
- fell (felling and tree fall) and processing (delimbing and cross cutting) (Tufts 1997, Hartsough and Cooper 1999, Hånell et al. 2000);
- processing and bunching (Wang and Haarlaa 2002);
- position, fell, tree fall, delimbing, and cross cutting (Eliasson 2000); and
- position (boom and position), felling, delimbing, cross cutting, and piling limbs and tree tops (Puttock et al. 2005).

Krpan and Poršinsky (2002) reported that the analysis of work time required for specific work components of felling and wood processing by a harvester showed no dependence between the time required and the size of the felled trees. Overall, it seems that delimbing time has been shown to be affected by the DBH of the harvested tree in all studies except that by Krpan and Poršinsky (2002).

The greater the DBH of the harvested tree, the greater the height (p for correlation coefficient < 0.0001, p for Y intercept < 0.0001) (**Fig. 3**). The greater the height of the harvested tree, the significantly longer the time for delimbing (**Fig. 4**) ($0.025 < p < 0.05$). It was also demonstrated that the greater the DBH of the the harvested tree, the slower the delimbing speed (**Fig. 5**) ($0.025 < p < 0.05$).

These results imply that the DBH of harvested trees affects the time for delimbing for two reasons: increasing tree height and hence increasing delimbing time with increasing DBH (**Figs. 3 and 4**) and decreasing delimbing speed with increasing DBH of the harvested tree (**Fig. 5**). McNeel and Ruther-

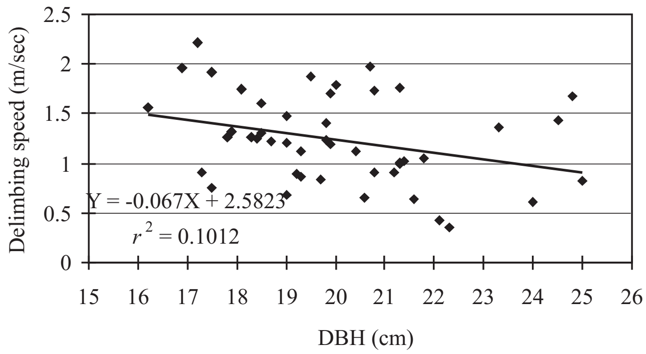

Figure 5. ~ *Simple linear regression analysis of delimbing speed on the DBH of the harvested tree.*

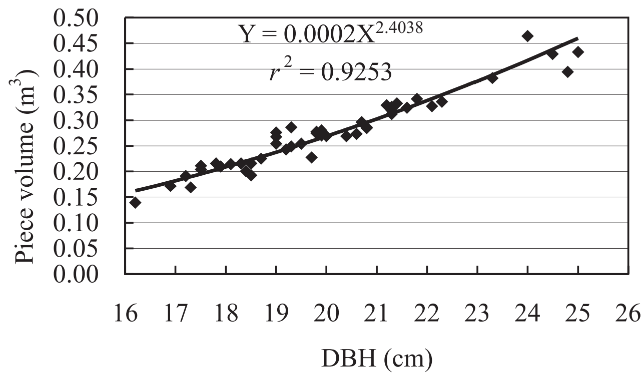

Figure 7. ~ *The relationship between DBH and piece volume.*

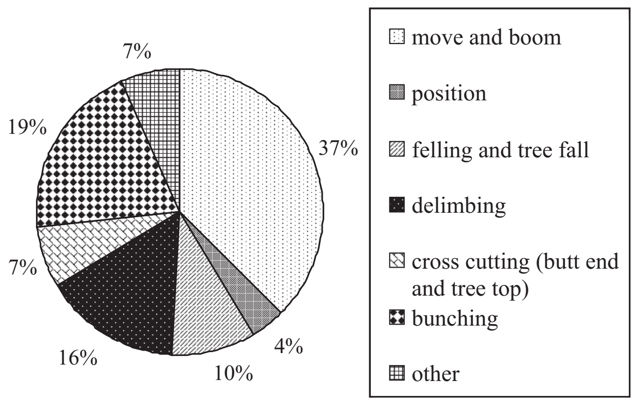

Figure 6. ~ *Proportions of work elements in total time to harvest one tree.*

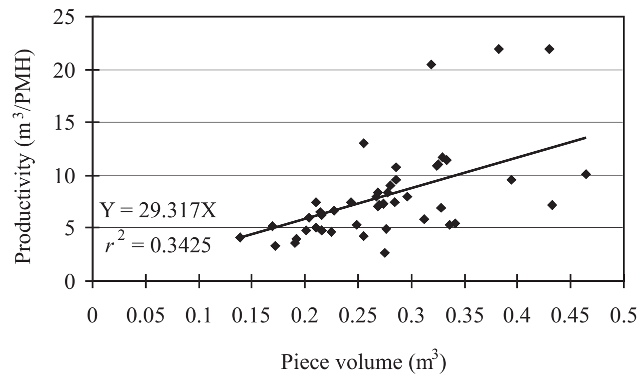

Figure 8. ~ *Simple linear regression analysis of harvester productivity on the piece volume of the harvested tree.*

ford (1994) and Sakai and Minamikata (1987) also reported that delimbing time was affected by the length of the tree stem.

Hydraulic power of excavators are much less than that of base machines specifically made for forestry operations (Sato 2005). Among all work elements performed by a harvester, delimbing requires the most hydraulic power. How to secure hydraulic power for this work element is always a problem for excavator-based harvesters (Hirohashi 2005, Kawakami 2005, Munakata 2005). Nakajima (1993) reported that the volume of branches of *Larix kaempferi* is about 21 percent of a stem volume. A larger number and size of branches could explain why delimbing speed became significantly slower with increasing DBH of the harvested tree in this study (**Fig. 5**).

Relatively low tree density could also be a reason why delimbing speed was affected by DBHs of harvested trees. At the study site, intensive thinning at an early age (Chujo 2004) resulted in a relatively low density of trees (**Table 1**) compared to a standard tree density (625 to 750 trees/ha) for the same age of plantation of the same species (Hokkaido Ringyo Kairyo Fukyu Kyokai 1981). Low tree density could have resulted in thicker branches of standing trees, which made delimbing a time consuming work element especially for larger diameter trees.

Even though time for delimbing was affected by the diameter of the harvested stems (**Fig. 2**), total time for handling one tree was not affect by the DBH of the harvested tree (**Table 4**). **Figure 6** shows the proportions of work elements. The most time consuming element was "move and boom." On average, only 16 percent of the total time was required for delimbing. The rest of the harvesting operation was not affected by the size of the harvested tree (**Table 4**).

Piece volume of the tree became larger as the diameter became thicker (p for correlation coefficient < 0.0001, p for Y intercept < 0.0001) (**Fig. 7**). Similarly, the productivity of the harvester became significantly higher as piece volumes of the harvested trees became thicker (p for regression coefficient = 0.0002, p for Y intercept = 0.8140) (**Fig. 8**). Harvester productivity was considered to be directly proportional to the piece volume of the harvested trees (**Fig. 8**), since the total time for one tree was not affected by the DBH of the harvested tree (**Table 4**). Harvester productivity was 9.2 m^3 per producive machine hour (PMH), about 33.4 times of piece volume, which was close to the regression coefficient (**Fig. 8**).

The result of the present study is contrary to what has already been reported; most researchers reported that piece volume affects the time needed to handle one tree by a harvester (Tufts and Brinker 1993, Tufts 1997, Eliasson et al. 1999, Eliasson 2000, Hånell et al. 2000, Wang and Haarlaa 2002). It was reported that harvester productivity would increase with increasing harvesting intensity in shelterwood harvesting because the distance to the nearest tree to be harvested becomes shorter (Eliasson 1999). It was also reported that time consumption for the average harvested tree would increase with a declining number of harvested trees per hectare because either or both move and boom per tree becomes longer (Eliasson and Lageson 1999, Eliasson et al. 1999, Eliasson 2000, Hånell et al. 2000, Suadicani and Fjeld 2001). The relatively large percentage (37%) of time consumed for move and boom in this study (**Fig. 6**) was due to the low percentage of thinning and hence wider distance between harvested trees (**Table 1**).

In addition, delimbing and cross cutting which were affected by DBH of the harvested tree in some other studies occupied a smaller portion of total time in this study because of the stem-length system, not cut-to-length system. It should also be noted that bunching occupies a significant portion of time in this study (**Fig. 6**). This is because whole stems were yarded by a skidder equipped with winches, not by a forwarder, and thus it was necessary to bunch stems to improve the productivity of yarding.

Delimbing time could occupy a larger portion of the total time in thinning with a greater harvesting rate or in clear cutting, in which the time required for move, boom, and bunching may be much less than that for the present study. In such a case, harvester productivity may not be linearly proportional to piece volume of the harvested tree; the slope of regression curve could become less steep with an increasing piece volume of harvested trees because a longer time is needed to delimb larger diameter trees.

This study demonstrated that there would be a case in which harvester productivity varied in a roughly linear manner proportional to piece volume of the harvested tree, because the time needed per tree is not affected by the DBH of the harvested tree in a low percentage of single tree selective thinning.

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