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ORIGINAL ARTICLE

Effect of tree size on time of each work element and processing productivity using an excavator-based single-grip harvester or processor at a landing

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Abstract We studied the effect of tree diameter at breast height (DBH) on the time required for the work elements in processing trees and on overall processing productivity at a landing. The times required for swinging with the tree, determining the butt-end cut, cutting the butt end, feeding and measuring, and cross-cutting were affected by the DBH of harvested trees. The time needed to process each tree was significantly longer for larger trees. However, the piece volume of trees increased as the diameter increased, and the rate of increase in volume was greater than the rate of increase in the time required to process one tree. Thus, processing productivity increased with increasing DBH (or piece volume) of harvested trees.

Keywords Bucking · DBH · Efficiency · Piece volume · Work element

Introduction

Forestry in Japan has become economically unprofitable because of weak timber prices, the increasing cost of reforestation, and forestry worker wages. To return profitability to the forestry industry, the cost of timber harvesting must be reduced. One way to accomplish this is to mechanize forestry work.

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In Hokkaido, the northernmost main island of Japan, mechanized tree felling using harvesters is possible in forests with gentle slopes. But processing at landings either by processors or by harvesters seems promising even in forests with steeper slopes. The main difference between harvesters and processors is the presence or absence of a tilt function: harvesters, which have a tilt function can fell standing trees whereas processors cannot. Consequently, harvesters are often also used as processors at landings in Hokkaido. In Hokkaido, most processors and harvesters are excavator-based and single-grip. The base machines of processors and harvesters in Hokkaido commonly have a 0.50-m^3 bucket capacity and weigh about 11–12 metric tons.

The slope angles of forests on other islands of Japan are much steeper than those of Hokkaido. On those islands, processing is usually performed on forest roads because creating large landings on steep slopes is difficult. Nowadays, harvesters are increasingly chosen over processors because their tilt function is useful in processing on forest roads with steep gradients. In fact, the number of harvesters working in Japan was 442 in 2005, 502 in 2006, and 558 in 2007, whereas the number of processors in the same years was 1002, 1042, and 1086 (Technical Development Promoting Section, Research and Conservation Division, Forestry Agency 2009); thus, the number of harvesters in use has been increasing more rapidly than has the number of processors.

A knowledge of processing productivity is essential for mechanization, because working hours and processing costs must be calculated. The effect of tree size on processing productivity by processors or harvesters needs to be described, because timber harvesting productivity is most affected by tree size (Puttock et al. 2005). The processing operation consists of several work elements, such as swinging without a tree, picking up, delimbing a whole tree, feeding and measuring, cross-cutting, and cleaning. Analyses of the work elements may lead to a better understanding of processing productivity based on tree size, and are useful to forestry mechanization in mountainous regions. However, few studies of the work elements involved in processing have been conducted (Hashira 2001); hence, application of the processing productivity of harvesters or processors based on tree size is still rare in private forests in Hokkaido. Here, we report the effect of tree size on the time required for specific work elements and processing productivity at a landing, to clarify the overall relationship between tree size and productivity.

Materials and methods

Study site

This study was conducted at a landing in compartment 60, sub-compartment 27, of a privately owned stand in Takinoue-cho, Hokkaido, the northernmost island of Japan; the stand was a 43-year-old, single species, even-aged plantation of Sachalin fir (*Abies sachalinensis* Masters). The mean diameter at breast height (DBH) of the stand was 19.8 cm, with a range of 10–40 cm, and the mean height was 13.7 m, with a range of 9–19 m. Figure 1 shows the height–diameter curve for the study site. In general, the greater the DBH was, the greater the height was. This stand was thinned out, resulting in an average piece volume of a harvested tree of 0.25 m^3, with a range of 0.056–0.529 m^3, and a mean DBH of 19.6 cm, with a range of 10–28 cm. The wood utilization percentage (log volume produced divided by timber volume) was about 74%.

Methods

Timber harvesting was performed on 1 February 2006. The trees were felled with chain saws and bunched by an excavator-based grapple saw. Whole trees were yarded using a tractor (crawler-type skidder equipped with winches) and processed at a landing by an excavator-based harvester (Timberjack 746B attached to a Komatsu PC138US) weighing about 12 metric tons. Four types of log were produced and sorted into different piles: 4.0-m saw logs, 3.65-m saw logs, 2.75-m saw logs, and 2.4-m pulp logs. Table 1 lists the price and typical use of Sachalin fir logs in Abashiri sub-prefecture, Hokkaido. The 4.0-m log pile was farthest from the harvester, the 3.65-m log pile was second farthest, the 2.75-m log pile was third farthest, and the closest was the 2.4-m pulp log pile. Delimbed branches were piled next to the 2.4-m pulp log pile and pushed off the landing by blading with the excavator every 30 min or so. The relationship between DBH and processing productivity, based partly on the data used by this study, was described by Kanzaki et al. (2006). The processing productivity increased as the DBH of harvested trees increased, a finding also reported by many others (Greene and Lanford 1985; Tan 1987; Araki 1992; Nakajima 1997). To understand this relationship between tree size and processing productivity better, we analyzed the effect of tree size on the time required for each work element.

We videotaped the processing of 10.24 m^3 of timber, comprising 41 trees, at the landing. Each tree was picked up and its butt end was cut off. It was fed, measured, and cross-cut to the appropriate length of each log type, and this cycle was repeated up to the top of the tree. Logs were dropped on piles after each cross-cut operation. Only eight whole trees were delimbed right to the tree top prior to feeding/measuring and cross-cutting.

Log lengths were recorded and the diameters of the top ends of the logs were calculated using the lengths of logs and a stem taper table. The volume of each log was calculated from its length and diameter. In the laboratory, we reviewed the videotapes to determine the time required for specific work elements, as shown in Table 2. When more than one work element was performed simultaneously, we assigned the higher priority work element. This happened frequently in determining the butt-end cut and in feeding and measuring; often the harvester first swung with the log, and then suddenly reduced the swinging speed and started feeding on to the rollers at the same time, because pulling stems through the harvester head using only the feed rollers was difficult. The cleaning time was distributed across all trees in proportion to the piece volume, because the volume of branches is roughly proportional to the tree piece volume (Nakashima 1993). The time for work element "other" was distributed equally to all trees. The time required for each work element for a specific tree was summed to calculate the total time required per tree. The processing productivity was calculated from the volume of logs per tree and the total time for each tree.

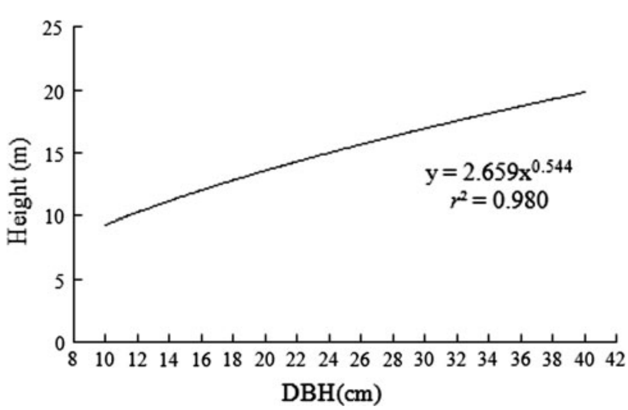

Fig. 1 Height–diameter curve for the study site

Table 1 Price and use of Sachalin fir logs in Abashiri sub-prefecture, Hokkaido

Length (m)	Top end diameter (cm)	Requirements	Price[a] (JPNYen/m^3)	Typical use[b]
3.65	14–18	Without rot, straight, not knotty	8,600	Construction, packaging, etc
3.65	20–22	Without rot, straight, not knotty	10,800	Construction, packaging, etc
3.65	24–28	Without rot, straight, not knotty	11,600	Construction, packaging, etc
3.65	30–38	Without rot, straight, not knotty	12,700	Construction, packaging, etc
2.75	12–18	Without rot, straight, not knotty	Not available	Construction, packaging, etc
2.75	20 or more	Without rot, straight, not knotty	Not available	Construction, packaging, etc
4.00	10 or more	Without rot, straight, not knotty	Not available	Construction, packaging, etc
2.40	6 or more		5,000	Pulp

[a] Based on Forestry and Lumber Promotion Division (2009a)

[b] Based on Forestry and Lumber Promotion Division (2009b)

Table 2 Description of work elements

Work element	Priority	Definition
Swinging without tree	1	Starts when a tree top is dumped and ends when the harvester head reaches a new tree to be processed
Picking up	1	Harvester picks up a log: starts when the harvester head reaches a new tree and ends when harvester starts swinging with the tree
Delimbing whole tree	1	Delimbing to the tree top without measuring; applicable only to a few trees
Swinging with tree	2	The harvester swings with the tree
Determining butt-end cut	1	Feeding the butt end in and deciding where to cut it
Cutting butt end	1	Cross-cutting the butt end (sloven) of the tree
Feeding and measuring	1	Feeding stems through and measuring the lengths of logs
Cross-cutting	1	Cross-cutting trees to specified log lengths
Tree top	1	Dumping the tree top
Cleaning	1	Dumping the branches
Other	2	All work elements that do not belong to the above categories

The effects of DBH on the time required for specific work elements, and the effects of DBH and piece volume on the total time per tree, were analyzed using simple linear regression analysis, as were the effects of the top-end diameter of logs on the time for work elements associated with particular logs. Because only three 4.0-m saw logs were produced during the study period, they were excluded from the analysis. The effects of DBH on the number of logs produced per tree and the effects of the number of logs produced on the total time per tree were also analyzed by simple linear regression analysis. The effects of DBH and piece volume on processing productivity were analyzed by simple two-parameter nonlinear regressions with power functions. Simple two-parameter nonlinear regressions with power functions were also used to analyze the rates of piece volume increase, time required to process one tree, and productivity. The level of significance for all statistical analysis was $p < 0.05$.

Results

Table 3 shows results from regression analysis of time for specific work elements per tree as functions of the DBH per processed tree. DBH affected the time of swinging with the tree, determining the butt-end cut, cutting the butt end, feeding and measuring, and cross-cutting. Thus, the time required to process one tree increased significantly with the DBH of the harvested tree ($p < 0.005$, Fig. 2), as it did with piece volume ($p < 0.0005$, Fig. 3).

Table 4 shows the types of logs produced during this study. Many butt logs and logs closer to butts were saw logs, whereas logs further away from butts were pulp logs.

Table 5 shows results from simple linear regression analysis of time for specific work elements per log as a function of log top-end diameter. The time for swinging with the tree, feeding and measuring 2.4 m, and cross-cutting were affected by the top-end diameter of the logs.

Table 3 Results from simple linear regression analysis of time of specific work elements per tree as a function of DBH (cm) of processed tree

Dependent variable: time (s)	*Y* intercept	Regression coefficient	*p*, regression coefficient	r^2	*n*
Swinging without tree	3.12	0.11	$0.05 < p < 0.10$	0.08	41
Picking up	–0.97	0.27	$0.05 < p < 0.10$	0.09	41
Delimbing whole tree	–34.64	1.90	$0.05 < p < 0.10$	0.48	8
Swinging with tree	–4.23	0.67	$p < 0.0005$	0.30	41
Determining butt-end cut	–2.97	0.43	$0.0025 < p < 0.005$	0.19	41
Cutting butt end	–0.55	0.17	$p < 0.0005$	0.40	41
Feeding and measuring	–2.53	0.73	$p < 0.0005$	0.45	41
Cross-cutting	–0.91	0.37	$p < 0.0005$	0.48	41
Tree top	0.31	0.15	$0.05 < p < 0.10$	0.07	41

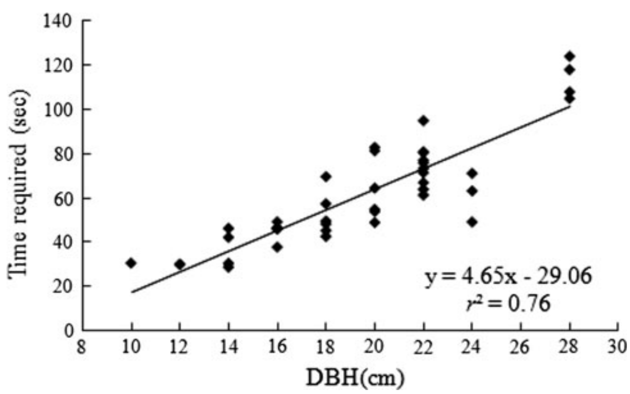

Fig. 2 Results from simple linear regression analysis of total time for one tree as a function of processed tree DBH ($n = 41$, regression coefficient $p < 0.0005$)

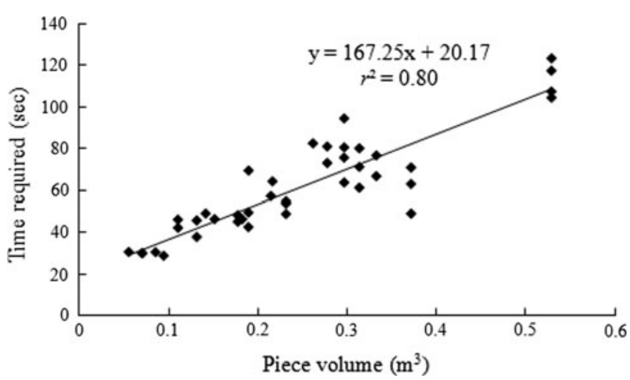

Fig. 3 Results from simple linear regression analysis of total time for one tree as a function of processed tree piece volume ($n = 41$, regression coefficient $p < 0.0005$)

Table 6 shows results from simple linear regression analysis of the number of logs produced per tree as a function of DBH, and the total processing time per tree as a function of the number of logs produced per tree. The number of logs produced per tree increased significantly with increasing DBH, and the processing time also increased significantly as the number of logs produced per tree increased.

Figure 4 shows the results from simple two-parameter nonlinear regression with power functions of productivity as a function of the DBH of processed trees, and Fig. 5 shows results from simple two-parameter nonlinear regression with power functions of productivity as a function of the piece volume of processed trees. Productivity increased significantly as DBH ($p < 0.0005$, Fig. 4) and piece volume ($p < 0.0005$, Fig. 5) increased. Processing productivity (m^3/productive machine hour, PMH) was estimated at $0.363 \times (\text{DBH [cm] of processed tree})^{1.116}$ (Fig. 4), or $20.46 \times (\text{piece volume [m}^3\text{] of processed tree})^{0.482}$ (Fig. 5). The processing productivity during this study was 10.78 m^3/PMH.

Figure 6 shows the proportion of time devoted to various work elements. The most time-consuming element was feeding and measuring, followed by swinging with the tree. If cleaning time is considered proportional to piece volume, about 68% of the total time was occupied with work elements that were affected by the size of trees to be processed (Table 3; Fig. 6).

Discussion

Our work elements results were similar to those reported by Hashira (2001), who reported that the time for delimbing and cross-cutting/piling (equivalent to swinging with the tree, feeding and measuring, and cross-cutting in this study) increased with increasing size of trees.

The effect of tree size on the time required for each harvester work element has been extensively studied. Because the processing and the cut-to-length system of harvesters include the same work elements, we referred to reports on harvesters. Feeding, measuring, and cross-cutting are the harvester work elements in the cut-to-length system that are affected by either the DBH or piece volume of harvested trees (Tufts and Brinker 1993; Tufts 1997; Hartsough and Cooper 1999; Eliasson 2000; Hånell et al.

Table 4 Number of each type of log produced during this study

Log position	4.00-m saw log	3.65-m saw log	2.75-m saw log	2.40-m pulp log
Butt log	3 logs, 0.138 m^3	17 logs, 1.902 m^3	8 logs, 0.639 m^3	13 logs, 0.790 m^3
2nd from butt		13 logs, 1.104 m^3	4 logs, 0.201 m^3	24 logs, 1.005 m^3
3rd from butt		1 log, 0.053 m^3	2 logs, 0.098 m^3	36 logs, 1.049 m^3
4th from butt				28 logs, 0.502 m^3
5th from butt				11 logs, 0.117 m^3
6th from butt				1 log, 0.009 m^3
Total	3 logs, 0.138 m^3	31 logs, 3.059 m^3	14 logs, 0.938 m^3	113 logs, 3.472 m^3

Table 5 Results from simple linear regression analysis of time for specific work elements per log as a function of top-end diameter of logs (cm)

Dependent variable: time (s)	*Y* intercept	Regression coefficient	*p*, regression coefficient	r^2	*n*
Swinging with tree being processed	0.70	0.07	$p < 0.0005$	0.07	184
Feeding and measuring 2.40 m	1.70	0.10	$0.01 < p < 0.025$	0.05	113
Feeding and measuring 2.75 m	9.18	–0.30	$0.05 < p < 0.10$	0.23	14
Feeding and measuring 3.65 m	4.20	–0.07	$p > 0.25$	0.04	31
Cross-cutting	0.71	0.08	$p < 0.0005$	0.26	161

Table 6 Results from simple linear regression analysis of number of logs produced from one tree as a function of DBH, and total time required to process one tree as a function of number of logs produced

Independent variable	Dependent variable	*Y* intercept	Regression coefficient	*p*, regression coefficient	r^2	*n*
DBH (cm) of tree	Number of logs produced per tree	1.54	0.121	$p < 0.0005$	0.33	41
Number of logs produced per tree	Total processing time per tree (s)	4.16	14.81	$p < 0.0005$	0.34	41

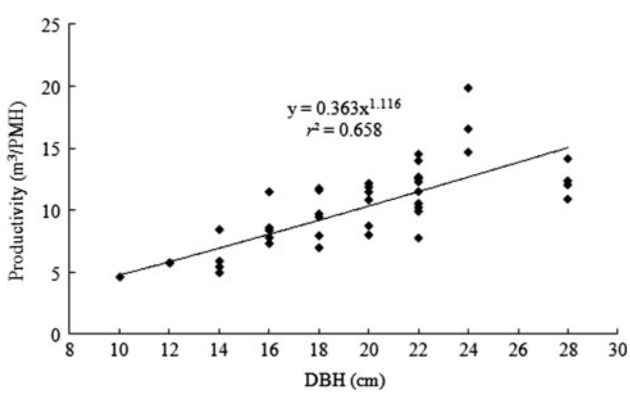

Fig. 4 Results from simple two-parameter nonlinear regressions with power functions of productivity as a function of processed tree DBH ($n = 41$, regression coefficient $p < 0.0005$)

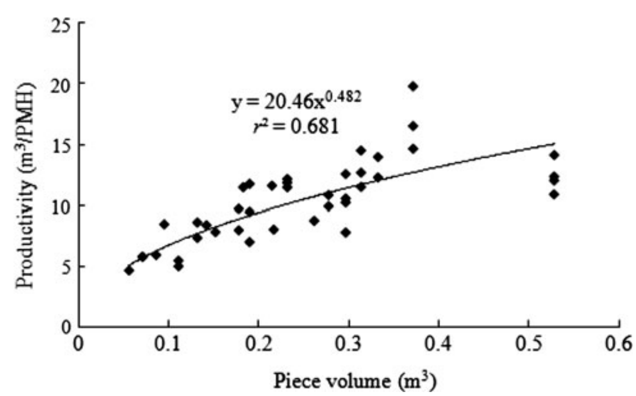

Fig. 5 Results from simple two-parameter nonlinear regressions with power functions of productivity as a function of piece volume of processed tree ($n = 41$, regression coefficient $p < 0.0005$)

2000; Suadicani and Fjeld 2001; Wang and Haarlaa 2002; Puttock et al. 2005). The results of our study are in accordance with the findings reported for harvesters in the cut-to-length system: determining the butt-end cut, cutting the butt end, feeding and measuring, and cross-cutting are all affected by tree size (Table 3).

These work elements seem to be affected by tree size for three reasons. First, the time required for determining the butt-end cut was affected by tree size (Table 3) because the butt ends were not straight, owing to snow, and slope steepness, making pulling the stems through the harvester head difficult. Second, the time required for cross-cutting was affected by the thickness of the log (Table 5). Third,

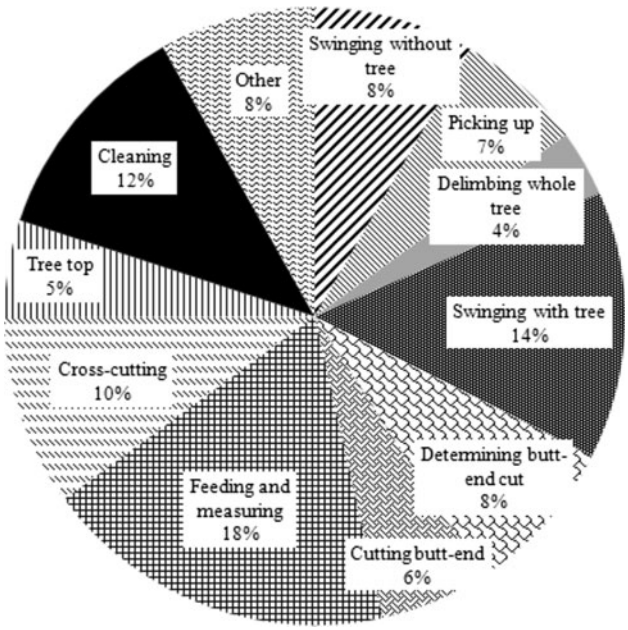

Fig. 6 Work element proportions of total time to process one tree

the number of logs produced increased with increasing DBH (Table 6) because tree height increased as the DBH increased (Fig. 1).

The time required for delimbing a whole tree was not significantly affected by the thickness of the tree. Because of the small sample size (only eight whole trees were delimbed during the study), we could not assess the effect of tree size on the time required for delimbing whole trees.

The time spent swinging with a tree was affected by tree size (Table 3) for two possible reasons. First, because the number of logs produced increases with the size of the tree (Table 6; Fig. 1), the amount of swinging with the tree would also increase. Second, the landing layout might also have been a factor. Saw-log piles were farther away from the harvesters than was the pulp-log pile. Because more saw logs were usually produced from larger trees, the harvester had to swing more often to the farther piles for larger trees, which demanded more swinging time per log of the tree being processed (Table 5).

Only the time for feeding and measuring the 2.4-m logs (but not the 2.75 or 3.65-m logs) was affected by log thickness (Table 5). There could be two reasons for this. First, if rot exists on the lower portion of the stem, then pulling the stem back and forth is required to find the best cutting length combinations for that portion; the operator wants to produce as many saw logs as possible and make only the rotten parts into pulp logs (Table 1). Second, if butt logs and the second logs from the butt are not straight, they become pulp logs (Table 1). Thicker crooked stems require more time to feed, just as determining the butt-end cut (Table 3) required more time.

Our findings on the relationship between tree size and total time required per tree agree with previous reports showing that the processing time per tree increased with tree size when using a single-grip processor (Greene and Lanford 1985), tractor-mounted processor (Sowa et al. 2007), or excavator-based single-grip processor (Tarnowski et al. 1999; Hashira 2001; Ishikawa et al. 2008).

Our results are also similar to findings on harvesting using the cut-to-length system in shelterwoods or clear-cutting sites; most researchers have reported that tree size affects the time needed to handle a tree (Tufts and Brinker 1993; Tufts 1997; Eliasson et al. 1999; Eliasson 2000; Hånell et al. 2000; Wang and Haarlaa 2002). On the other hand, Nakagawa et al. (2007) reported that the time required to handle one tree in single-tree qualitative thinning using the tree-length system was not strongly affected by tree size. The different effects of tree size on the time required for one tree can be explained by the different composition of work elements. Nakagawa et al. (2007) found that in single-tree qualitative thinning by a harvester, delimbing, which is the only work element affected by tree size, consumed only 16% of the total time. Thus, the increased time needed for delimbing larger trees was masked by fluctuations in the time required for other work elements. A larger proportion of the total time was required for moving and booming to the next tree to be harvested and bunching to increase whole-stem yarding productivity (Nakagawa et al. 2007). On the other hand, the percentage of time required for moving, booming, and bunching was small, and hence the percentage required for cross-cutting and feeding/measuring was large in the cut-to-length system of shelterwoods or clear-cutting. According to Eliasson (2000), the percentage of time required for work elements affected by tree size ranged from 66 to 76% for harvesters in the cut-to-length system. In processing, no time was needed for moving, booming, or bunching. In our study, more than half of the total time was taken up by work elements that were affected by tree size (Fig. 6; Table 3). The composition of work elements for harvesters in the cut-to-length system of shelterwood or clear-cutting and for processors is similar: a relatively large proportion of the total time is spent on work elements that are affected by tree size. Thus, a significantly longer time is needed to process larger trees (Figs. 2, 3).

Nonetheless, the piece volume of trees increased as the diameter increased, and the rate of increase in volume was greater than the rate of increase in the time required to process one tree (Fig. 7). Thus, processing productivity increased with the DBH or piece volume of harvested trees (Figs. 4, 5).

Figures 8 and 9 show the processing productivities of harvester and processors reported in earlier studies. The numbers in Fig. 9 indicate examples of productivity in

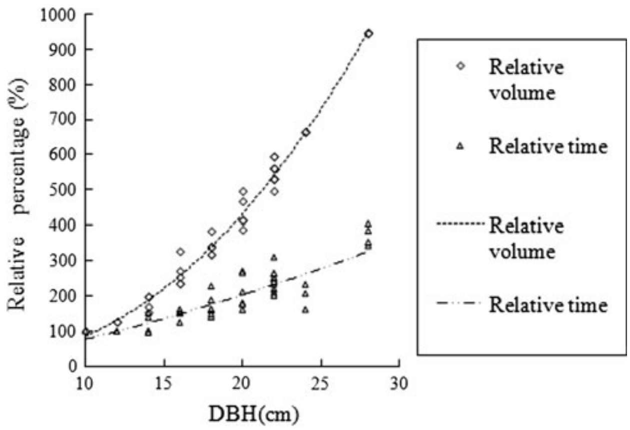

Fig. 7 Rate of increase for piece volume and time required to process one tree (smallest diameter was set to 100%)

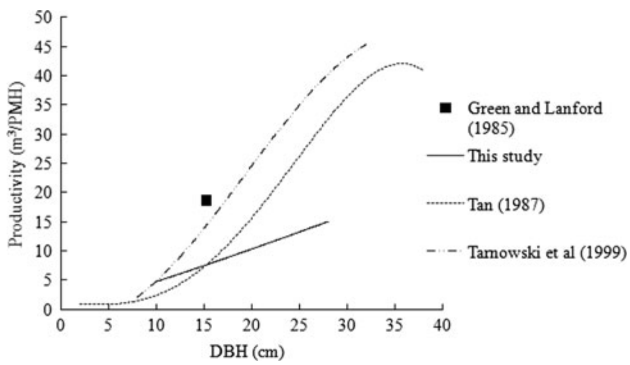

Fig. 8 Comparison of processing productivity with other reports based on DBH

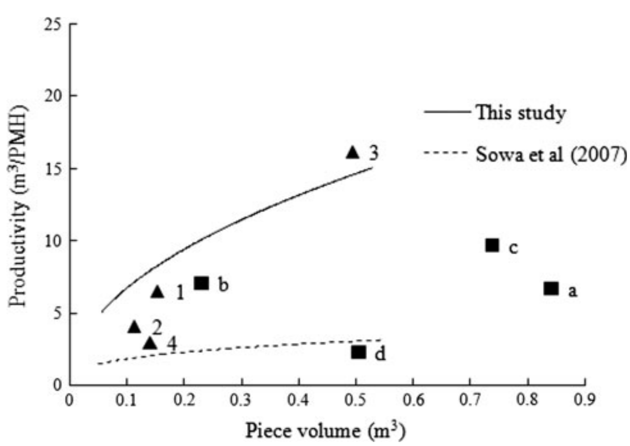

Fig. 9 Comparison of processing productivity with those from other reports based on piece volume. *1* Arakawa (1989), *2* Kohata (2001), *3* Kohata (2002), *4* Kohata et al. (1994), *a* Furukawa (2003), *b* Hatano (2003), *c* Ishikawa et al. (2008), and *d* Taniguchi et al. (2002)

Hokkaido, and the letters indicate those in other Japanese islands where forests are usually located on steeper sites and processing by processor or harvesters is usually done on narrow forest roads. With the exception of DBH less than 15 cm in Tan's report (1987), the processing productivity observed in our study were much less than those achieved by processors with base machines specifically made for forestry use (Greene and Lanford 1985; Tan 1987) or by processors with an excavator much bigger than that considered in our study (Tarnowski et al. 1999). On the other hand, the productivity observed in our study was much higher than the productivity achieved by a processor with a farm tractor (Sowa et al. 2007). Although using small excavators as base machines is much better than using farm tractors, this may result in lower processing productivity. The productivity observed in our study was much higher than that achieved on other Japanese islands. This implies that using harvesters and processors on large landings is better than using them on narrow forest roads.

Because the results of our study were based on just one observation, caution is required when applying the formulas shown in Figs. 4 or 5 to estimate the processing productivity in Hokkaido; only one study reported higher productivity than this study and others reported lower productivity (Fig. 9). In addition, the results of this study may only be applied to processing of trees with 10–28-cm DBH, to avoid extrapolation of regression results. More productivity studies with wide ranges of tree size are required to develop a standard productivity table for processing by processors or harvesters with 11-metric-ton excavators as base machines at landings in Hokkaido. Such a table should include tree size as a major factor. If such a table were developed, much more accurate estimation of processing productivity and processing cost using an excavator-based single-grip harvester or processor at a landing would be possible in Hokkaido. We believe that the results of this study would be useful for helping prospective developers and users of such a productivity table to understand the relationship between tree size and processing productivity.

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