Effects of Thinning Type on the Harvester Productivity and on the Residual Stand

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ABSTRACT

Harvester productivity, extraction rate, selection criteria for harvesting a tree, and logging damage after different thinning types were studied in northern Sweden. Thinning operations were mechanized and carried out according to normal Swedish practice. The treatments were supervised thinning from below, supervised thinning from above, and unsupervised thinning from above. Time consumption per tree and harvester productivity in thinning from below were significantly different from thinning from above. Extraction rate was higher than the desired level in one plot for unsupervised thinning from above. One plot had a thinning ratio high enough to fit the definition for thinning from above, due to trees harvested independently of thinning type. Mean diameter for damaged and suppressed trees harvested was not different between treatments. No differences in the frequency for size and type of logging damage was found between treatments. For thinning from below, damage was located higher up on the stem than for thinning from above. This study concludes that differences in thinning ratio may be reduced when carried out in commercial forestry, due to the harvest of damaged, suppressed, and, to some extent, strip road trees. Harvester productivity increases with increased thinning ratio. To attain the desired stand densities and to keep damage level down, a skilled and motivated harvester operator is needed.

Keywords: *Extraction rate, logging damage, thinning ratio, time study, tree-type.*

INTRODUCTION

Swedish logging operations are dominated by the cut-to-length system [4]. In 1991/92, 54.0% of the volume extracted came from final fellings, 28.5% from commercial thinnings, 1.5% from pre-commercial thinnings, and 16% from other fellings [5]. Logging operations are almost completely mechanized. Single- and double-grip harvesters do most of the felling, debranching, and cross-cutting, and hauling to roadside is dominated by forwarders [4]. Single-grip harvesters dominate thinning and are common in clear felling, while double-grip harvesters are used almost exclusively for clear felling.

Traditionally, thinning from below has been the dominating thinning type [17]. Interest in other thinning types is, however, on the increase in Scandinavia and Finland. Thinning from above is believed to increase profits and enhance timber quality in the residual stand [6, 20]. Thinning types can be defined by using the thinning ratio, i.e. the ratio between mean diameter at breast height (DBH) of trees extracted to residual trees. When thinning from above, the mean DBH of trees removed is larger than that of residual trees (cf. [25]) and consequently, thinning ratio exceeds 1.0.

Productivity (m^3 per productive machine hour (PMH)) of a harvester depends on several factors, e.g., machine type, average tree size, stand density, extraction rate, (i.e., the ratio between basal area harvested and basal area before harvest), slope, ground conditions, and skill of operator [9, 23]. When thinning from above, harvester productivity increases and time consumption per volume unit decreases, as trees harvested are bigger [12]. An exception to this general relationship is exceptional trees with large branches (cf. [24]). Given increased tree size harvesting, productivity is correlated to reduced harvesting costs [17, 22].

A hazard when thinning from above [22] is that the basal area is easily reduced below the level desired when large trees are extracted, leading to future yield losses. Therefore, operator skill and motivation is very important.

According to normal Swedish practice (mechanized selective thinning), first thinning includes cutting strip road trees [4]. A varying amount of more-or-less severely damaged or diseased trees are also extracted. Therefore, a large number of the extracted trees will be removed irrespective of thinning type.

When thinning, residual trees risk getting damaged by harvesters and forwarders [7, 13]. Others, however, found no differences in logging damage between different thinning types [16, 22].

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The aim of this study was to analyse harvester productivity, extraction rates, criteria for selecting trees to harvest, and damage levels after thinning from below and above. Harvesting operations followed normal Swedish practice.

MATERIALS AND METHODS

The experimental sites were located at two places in northern Sweden, Hemmesmark (64°06'N, 20°20'E) at an altitude of 115 m a.s.l. and Gagsmark (65°08'N, 21°16'E) at an altitude of 95 m a.s.l. Scots pine (*Pinus sylvestris* L.) was the dominant tree-species at both locations. The stand in Hemmesmark was established between 1935 and 1945 by advance growth and supplementary natural regeneration. The site index (SI_{100}) was estimated to 21 (a dominant height 21 m at 100 years of age [15]). The stand in Gagsmark was selectively logged between 1933 and 1936, leaving a residual basal area of approximately 10 $m^2 ha^{-1}$. Between 1939 and 1945 the remaining trees were harvested. The present stand was established by advance growth and supplementary natural regeneration and was pre-commercially thinned (cleaned) in 1964. The site index (SI_{100}) was estimated to 22. The soil at both locations is mesic sandy silty till, with ground vegetation dominated by *Vaccinium myrtillus* L. and *V. vitis-idaéa* L.

A block design with three randomized treatments (plots) and three replications (blocks) was used. One block was located in Hemmesmark and two in Gagsmark. The two blocks in Gagsmark were adjacent and plots were adjacent in all blocks. Plots were 25 m wide and 130 to 175 m long. The average slope for the blocks varied between 1 and 4° (2–7%). Total enumeration of the plots was carried out before logging.

The treatments were supervised thinning from below (STB), supervised thinning from above (STA), and unsupervised thinning from above (UTA). For STB and STA, trees to be cut were marked prior to logging. For UTA, a written thinning-instruction was given to the harvester operator. Damaged trees, i.e., trees with bark partly removed and with broken or dying tops due to rust fungus (*Endocronartium pini* (Pers.) Lév. ex Hiratsuka) and strip road trees were cut first for all treatments. For STB, subdominant and codominant trees were selected for cutting according to quality, vitality, and species. For STA and UTA, dominant and codominant trees of poor quality were cut. Suppressed trees were left unless they were obstacles to logging. Strip roads were not marked in the field. When possible, the operator placed them in natural gaps in the plots. Their exact location was also, to some extent, dependent on the treatment, i.e., leaving larger trees for STB compared to STA and UTA. Mean strip road width was 4.3 m for all treatments.

Desired residual stand density was 17 $m^2 ha^{-1}$ in Hemmesmark, and 20 $m^2 ha^{-1}$ in Gagsmark, irrespective of thinning type, which corresponds to 30% removal of the basal area. The unmarked treatment, UTA, was used to investigate the operators ability in attaining the desired stand density.

Logging was carried out by single-grip harvesters. Hemmesmark was logged in late May using an ÖSA 260/752; Gagsmark was logged in August using a Valmet 862/942. Different operators were used in Hemmesmark and Gagsmark. Both operators had a long experience of operating their harvesters. The operator in Gagsmark was more experienced in thinning operations. None of them had any experience of thinning from above. In Hemmesmark, where the stand was dense, the operator felled the trees not reached by the harvester with a chainsaw and used the machine as a processor. These trees are not included in the productivity study. During the logging operation, DBH of all trees extracted was recorded. Diameter distribution in the stand after thinning was calculated by subtracting the trees extracted from pre-logging stand data (Table 1).

A time study to analyse productivity of the harvesters for the different thinning types was conducted. Time study method used was repetitive timing [2]. In block 1, data were recorded with a special time study program, SIWORK3 [1], run on a Husky Hunter computer. In blocks 2 and 3 a centiminute (cmin) stop-watch was used. Elements used in the time study are shown in Table 2.

During logging, criteria for selecting trees for harvest were recorded. Harvested trees were divided into four types, (1) normal, (2) strip road, (3) damaged, and (4) suppressed. In this study, a tree denoted as normal was an undamaged non-suppressed tree not standing in the strip road. After logging, all residual trees were checked for damage caused by harvesters. Damage was divided into three size classes (DS) : (1) <20 cm^2, (2) $\geq 20 < 100$ cm^2, and (3) ≥ 100 cm^2; three locations (DL): (1) root

Table 1. Stand data before, after, and from the extraction for the treatments; supervised thinning from below (STB), supervised thinning from above (STA) and unsupervised thinning from above (UTA).

	Block 1			2			3		
	STB	**STA**	**UTA**	**STB**	**STA**	**UTA**	**STB**	**STA**	**UTA**
Before Treatment									
Trees, ha^{-1}	1801	1893	1854	1148	967	927	1418	1171	1123
Mean Diameter (DBH), cm	11.8	11.4	11.4	17.0	18.4	18.6	15.6	17.3	17.9
Volume[a], m^3 ha^{-1}	159	155	153	238	243	236	245	259	262
Basal area, m^2 ha^{-1}	24.1	23.6	23.3	28.7	28.9	27.9	30.2	31.2	31.2
After Treatment									
Trees, ha^{-1}	993	1352	1119	635	636	657	772	750	723
Mean Diameter (DBH), cm	13.5	11.2	11.5	19.4	18.6	19.4	17.8	17.4	18.2
Volume[a], m^3 ha^{-1}	112	106	93	169	166	179	172	168	172
Basal area, m^2 ha^{-1}	16.5	16.1	14.2	19.8	19.6	21.0	20.6	20.3	20.3
Extraction									
Trees, ha^{-1}	808	541	735	513	331	270	646	421	400
Mean Diameter (DBH), cm	10.1	12.2	11.4	14.2	17.8	16.9	13.1	17.0	17.4
Volume[a], m^3 ha^{-1}	47	49	60	69	77	57	73	91	90
Basal area, m^2 ha^{-1}	7.6	7.5	9.1	8.9	9.3	6.9	9.6	10.9	10.9
Thinning ratio[b]	0.75	1.09	0.99	0.73	0.96	0.87	0.74	0.98	0.96
Treatment size, m^2	4375	4375	4375	4375	3375	3000	3250	3750	3750

[a]Volume, solid on bark, according to [21].
[b] Thinning ratio is mean diameter (DBH) of extracted trees divided by mean diameter of the residual trees (After Treatment).

Table 2. Elements of the harvester time study.

Moving:	Begins when the harvester starts to move, ends when the harvester stops moving to perform some task.
Processing:	Begins when the boom starts to swing towards a tree, ends when processing of a tree is complete and felling head have dropped the tree top. Includes felling, dropping the tree, and boom in.
Miscellaneous:	Elements disturbing the operational time, e.g., removal of saplings and brush and felling of unmerchantable trees, piling or sorting logs in the forest, handling slash or debris.
Delays:	Operational, mechanical, and personal delays that interupt the normal work activity of the harvester.

collar, (2) root collar to 2.0 m height, and (3) above 2 m; and two types of damage (DT): (1) bark peel-off and (2) splint damage (cf. [14]). A tree was denoted as damaged if bark was peeled-off and wood exposed. Root collar damage was an injury situated below a future felling cut within 0.7 m from the stem base. A splint damage was damage to wood tissue, situated inside an area where bark is peeled-off. When calculating the frequency of damaged trees in the experiment, only trees with a damage size larger than 20 cm^2 were recorded. Damage smaller than 20 cm^2 is difficult to detect, especially when situated high on stems.

To analyse the effect of different treatments on time consumption and mean DBH of harvested trees in different tree-types, Tukeys studentized range test (for balanced test) and analyses of variance were carried out on continuous variables, using SAS procedure GLM [3]. For frequency of trees in different tree-types and for the discrete variables, DS, DL, and DT, χ^2-tests were carried out. To be able to perform an accurate χ^2-test, the types of DS were combined into damaged and not damaged, and DL was combined into damage below and above 2 m. If $p < 0.05$, the result of the statistical analysis was called significant.

RESULTS

High thinning ratio in the thinning operation is correlated with high harvester productivity (m^3 solid under bark PMH^{-1}) (cf. Tables 1 and 3). Thinning ratios were 24 to 31% higher for thinning from above than for thinning from below. Hence, fewer trees with higher mean diameter were harvested when thinned from above (Table 1). Only treatment STA, block 1, had a thinning ratio higher than 1.0. Consequently, only in block 1 does STA fit the definition for thinning from above (cf. Introduction).

Residual stand density is an indicator of operator performance in thinning, with and without any marked trees (Table 1). Only in block 1, for UTA, the extraction rate was too high, compared to the desired stand density.

Time consumption in centiminutes (cmin) per tree for thinning from below was lower than for thinning from above, however, harvester productivity was higher for thinning from above (Table 3). Productivity was for STA 39% and for UTA 22% higher than STB. The element processing for STB was significantly different from STA and UTA, and in total STB was significantly different from STA and UTA (Table 3). The increase of time consumption per tree over diameter is shown in Figure 1. No significant differences for the linear regressions between the treatments in each block were found.

Table 3. Time consumption (cmin $tree^{-1}$) and harvester productivity for the treatments. Data for different treatments not followed by the same letter are significantly different ($p < 0.05$). For definition of the elements see Table 2.

	Treatment		
Variable	**STB**	**STA**	**UTA**
Move	10.7A	15.2A	13.2A
Processing	37.6A	43.3B	44.8B
Miscellaneous	0.5A	0.1A	1.3A
Total	48.7A	58.6B	59.2B
Productivity[a], (m^3s.u.b. PMH^{-1})	10.7A	14.9B	13.1B

[a] Volume, solid under bark (s.u.b.), according to [8].

Harvested trees were divided into different tree-types (Table 4). A lower frequency of normal trees was harvested in treatments STA and UTA, but no significant differences in frequency between treatments were shown. Mean diameter for normal trees was significantly different for all three treatments, and for strip road trees, treatment STB was significantly different from STA. For damaged and suppressed trees, no significant differences between treatments were found.

There were no significant differences between treatments in frequency for size and type of logging damage, and for treatment STB, damages were located higher up on stems compared to STA and UTA (Table 5).

Table 4. Frequency (%) of trees and mean diameter at breast height (DBH) for harvested trees in different tree-types. Data for mean DBH for different treatments not followed by the same letter are significantly different (p <0.05).

	Treatment					
	STB		STA		UTA	
Tree-type	%	mean DBH (cm)	%	mean DBH (cm)	%	mean DBH (cm)
Normal	62.7	12.1A	49.5	16.8B	49.4	15.0C
Strip road	23.8	12.8A	28.3	15.0B	33.5	14.3AB
Damaged	7.6	15.5A	11.7	16.5A	7.8	14.7A
Suppressed	5.9	10.7A	10.5	11.7A	9.3	10.3A

Table 5. Frequency (%) of damaged trees divided into size classes (DS), location (DL), and type (DT) of damage on affected trees.

	Treatment		
Variable	STB (%)	STA (%)	UTA (%)
DS≥20<100cm^2	4.0	3.9	3.4
DS≥100cm^2	1.0	0.7	2.3
Frequency damaged trees	5.0	4.6	5.7
DL root collar	4.8	17.5	18.4
DL root collar to 2m	62.2	70.2	61.5
DL above 2.0m	33.0	12.3	20.1
Sum DL	100.0	100.0	100.0
DT bark peel-off	91.3	88.5	85.1
DT splint damage	8.7	11.5	14.9
Sum DT	100.0	100.0	100.0

DISCUSSION

Thinning ratio in the first thinning depends on (1) strip road width, (2) spacing between strip roads, (3) extraction rate, (4) stand structure, and (5) thinning type. This experiment was designed to reduce the effects of factors 1 to 4, thus facilitating evaluation of the thinning type. This was achieved by using only one strip road of the same width in each plot, by setting basal area targets blockwise, and by selecting stands of similar structure.

Only one of the treatments, thinning from above in block 1, had a thinning ratio high enough to fit the definition (Table 1). Many trees harvested were strip road trees, damaged, and suppressed trees (Table 4). These trees were harvested irrespective of thinning type. Hence, only normal and, to some extent, strip road trees were selected differently owing to thinning type (Table 4). With the large amount of trees harvested independently of thinning type, differences in thinning ratio between thinning types were reduced. Differences between thinning types for the tree-types might have been larger if differences in thinning ratio had been larger, i.e., a ratio above 1.0 for thinning from above, or with higher basal area removal.

High thinning rates, i.e., high reduction of basal area, reduce the annual volume increment [10]. Basal area is easily reduced when thinning from above, especially with great variation in the diameter distribution [22]. Therefore, when comparing the two different thinning types, it is important that the basal area is equal after logging. The operator with greater experience of thinning (blocks 2 and 3) managed to attain the desired stand density, for UTA, better than the less experienced operator (block 1), despite greater variation in diameter for harvested trees (Figure 1). Block 1 was more densely stocked (trees ha^{-1}) than the other two blocks (Table 1) and, therefore, long experience of commercial thinning, especially thinning from above in dense stands, is important for not reducing the basal area too much.

Harvesting small trees is less time consuming than harvesting bigger trees [9, 12, 26]. Increases in mean diameter when logging led to increases in time consumption (cmin tree^{-1}). However, the increase in time consumption per tree was proportionally lower than that of diameter (Figure 1), which leads to higher productivity when thinning from above (Table 4, cf. [18]). Trees with the same mean diameter have, independently of thinning type, approximately the same time consumption for processing (cf. Figure 1 and [22]). There were also small differences in processing between marked (STA) and unmarked (UTA) treatments (Table 4, cf. [18]).

The low r^2 values for block 1 (Figure 1), compared to blocks 2 and 3, can be explained by a less experienced operator and a more dense stand. In dense stands, large variation in time consumption for the elements boom out, felling, and processing can be expected, when care not to damage the residual trees must be taken.

Time consumption (cmin tree^{-1}) for the element moving is dependent on terrain classification and on the number of trees harvested [9]. Since terrain conditions were similar between and within blocks, only the number of trees harvested per hectare varied. When the amount of harvested trees increases, time consumption for moving decreases (Table 3). Therefore, time consumption for moving is higher when thinning from above compared to thinning from below, due to fewer harvested trees (cf. [11]).

There was a low frequency of trees damaged by harvesting operations in this study and no differences between treatments were found (Table 5). Trees damaged by forwarder operations are not included, therefore, higher damage frequency for the entire logging operation, i.e., harvesting and forwarding, can be expected (cf. [16]). Damage levels might have been lower if operations had been carried out during another time of the year. In this study, block 1 was logged in late May and blocks 2 and 3 in August. Damage level is highest in June and August [14]. During summer, when the bark attachment to the wood is weakened, logging operations cause larger and deeper areas of damage than during other seasons [19, 27]. However, the most important factor determining the level of damage may be the skill and motivation of harvester and forwarder operators.

The location of damage in this study differs between thinning types. In thinning from above, damage is located lower than thinning from below. A possible explanation is that large trees are heavier and therefore more difficult to handle for the harvester when processing, especially in thinning from above where fewer trees are harvested leaving a denser stand than when thinning from below. Large trees also have larger branches which could damage residual trees when processed.

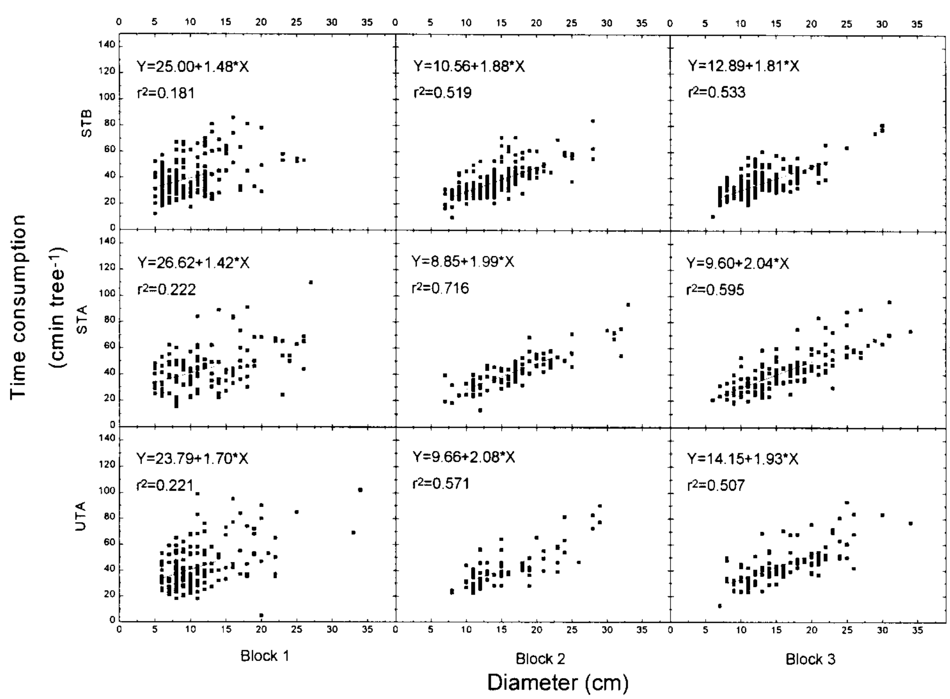

Figure 1. Time consumption per tree for element processing over diameter for the treatments in all blocks.

This study shows that differences in thinning types, i.e., thinning ratio, as applied in first thinning may be reduced when carried out in commercial forestry, mainly due to the harvest of damaged, suppressed, and, to some extent, strip road trees. Therefore, the ratio will often be less than 1.0 in first thinnings when conducted as thinning from above. Harvester productivity increases with increased thinning ratio. To reach the desired stand density, a skilled and motivated harvester operator is needed, otherwise future volume increment may be jeopardized.

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