Time Consumption and Damage to the Remaining Stock in Mechanised and Motor Manual Pre-Commercial Thinning

Daniel Ligné, Lars Eliasson and Tomas Nordfjell

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Selective pre-commercial thinning (PCT) is usually carried out by workers with a brush saw in order to increase the growth of the potential crop trees (main stems) through removal of competing trees. In the last decade relative PCT costs have increased, partly because stands are denser and have higher trees when treated, which has led to new interest for mechanised PCT. The objective was to compare mechanised and motor manual PCT regarding productivity and damage to remaining main stems. Time consumption for, and damage after, mechanised and motor manual PCT were studied on 50 plots per treatment in mixed pine birch stands with an initial stand density exceeding 4500 stems ha^{-1}. In the present study productivity was influenced by stand density, stand height and the quota between height and diameter. Irrespectively of these factors, mechanised PCT was 0.74 hours ha^{-1} slower than motor manual PCT. Motor manual PCT of the average stand (average height 3.69 m, 10 816 stems ha^{-1}) took 5.06 effective hours. In average 2475 and 2805 main stems ha^{-1} were left after the mechanised and motor manual treatments, respectively, whereof 1.3 and 2.1% were damaged by the treatments. The results show that efficiency in motor manual PCT has increased in dense and tall stands compared to older studies. Motor manual PCT was more time effective than mechanised PCT, and thereby also even more cost-effective. However, the potential for technical and methodological development of mechanised PCT is probably larger than for motor manual PCT.

Keywords brush saw, cleaning, Husqvarna, Scots pine, birch, time study, Vimek
Authors' addresses Swedish University of Agricultural Sciences, Department of Silviculture, SE-901 83 Umeå, Sweden **E-mail** lars.eliasson@norraskogsagarna.se
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1 Introduction

Selective pre-commercial thinning (PCT), carried out by workers with a brush saw, has been a common silvicultural treatment in Sweden since the 1950s (Bäckström 1984, Marntell 1989). It is generally made in order to increase growth of potential crop trees (main stems) through the removal of competing trees. A steady rise in the relative cost for pre-commercial thinning (Ligné et al. in press), and difficulties in attracting personnel to do motor manual work (Glöde and Bergkvist 2003), has highlighted the need for new techniques for pre-commercial thinning (cf. Ryans 1988, Freij 1991).

According to previous studies (Lidberg and Svensson 1971, Bergstrand et al. 1986) the two major factors influencing productivity for motor manual PCT with a brush saw are number of stems removed per ha and their average height. These factors have changed significantly during the last decade, as PCT tends to be performed in older stands than those of the early nineties, partly because the precommercially thinned area have declined in recent decades (Nilsson and Gustavsson 1999, Forestry Statistics… 2002), so stems to be cut tend to be taller and thicker. An increase in disturbed area, due to changes in scarification techniques during the 1980ies, give increased numbers of primarily naturally regenerated broadleaved trees per ha in today's PCT stands (cf. Forestry Statistics… 2002). This has created a need for new studies of the productivity for motor manual work with the brush saw, since earlier studies were made under different conditions than those prevailing today (cf. Lidberg and Svensson 1971, Bergstrand et al. 1986), and with older types of brush saws.

In the late eighties a number of machines for mechanised PCT were developed, most of these machines were designed to straddle a plant row and they were equipped with a cleaning head mounted in the tip of a crane. Field studies showed that these machines began to be economically competitive with motor manual workers at stand densities exceeding 10 000–13 000 stems ha^{-1} (Lindman and Nilsson 1989, Freij 1991). A problem with straddling machines was that 6 to 10% of the remaining main stems were damaged (Wästerlund 1988, 1990, Freij 1991), and another that they could not operate in stands higher than twice the ground clearance of the machine, i.e. stands higher than ca. 2 meters (Freij 1991).

Another approach is to drive the machine between the stems not to be cut; such a machine is henceforth referred to as a winding machine. Studies of PCT with winding machines reveal somewhat lower levels of damage, 3 to 8% of remaining main stems (Andersson and Mattsson 1993). Since the average height of the remaining stems at the time for PCT is about 4 meters today, a winding machine is probably necessary if selective PCT is to be mechanised. The Vimek 404R is a winding machine, where articulated steering between the front and rear part of the machine is combined with a single-axle with Ackerman-steering on the front part. The two steering systems give the machine an unusually small turning radius (2.2 m). The 2.8 Mg machine is 1.6 m wide and has a parallel boom with a reach of 5 m, at

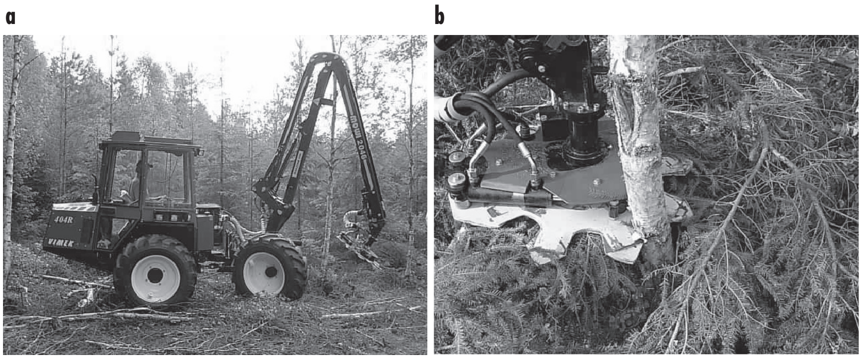

Fig. 1. a) The Vimek 404R b) The cutting head for pre-commercial thinning.

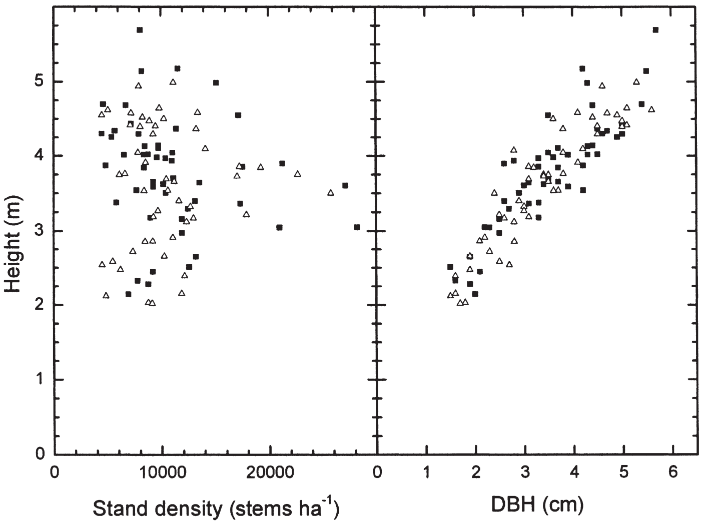

Fig. 2. Average stand height versus stand density and average diameter at breast height (DBH). Plot treated with motor manual PCT represented by filled squares and plots treated with mechanised PCT by triangles.

the tip of the boom there is a Vimek shear type cutting head (Fig. 1). This is a new type of cutting device for PCT based on a shear technique that can be geared up and down, depending on resistance (Ligné et al. in press).

An experimental study of the Vimek machine and four motor manual tools made in artificial stands (Ligné et al. in press), showed that mechanised PCT might prove a good alternative to motor manual work in dense (> 15 000 stems ha^{-1}) stands with stump diameter above 4 cm in terms of work efficiency and damage to remaining main stems. However, field tests are necessary to confirm these results.

The objective of this study was to compare mechanised and motor manual PCT regarding productivity and damage to remaining main stems. Furthermore, an analysis of what factors that influences time consumption for the two tools, respectively, was included.

2 Materials and Methods

The study was made in five stands along a road close to Åsträsk in Västerbotten, Sweden (lat. 64°60´N, long. 20°00´E, alt. 275 m a.s.l.). The stands were planted with Scots pine (*Pinus sylvestris* L.) but more than 80% of the stems were naturally regenerated downy birch (*Betula pubescens* Ehrh.). In these stands 100 plots with more than 4500 stems ha^{-1}, i.e. an estimated need for pre-commercial thinning, were established. As earlier studies have shown that stand density and stand mean height are the most important influencing variables, the 100 plots were sorted in five groups based on mean height. In each group plots were sorted after stand density into 10 subgroups. Within every subgroup, the two methods of PCT were randomly assigned to the plots. This should ensure an even and comparable variation of stand densities and mean heights for the two PCT methods studied (Fig. 2).

The plots were 6 m × 20 m (120 m^2) rectangles, each plot was subdivided into 4 parts of 6 m × 5 m to get a measure of the homogeneity of the plot. In each part of the plot the number of stems was counted and species recorded. After counting, height (cm) and diameter at breast height (mm) were recorded for 40 systematically selected sample trees in each plot. In each plot, ground strength, surface structure and slope (Table 1) was classified according to the Swedish system

Table 1. Number of plots in each treatment separated on slope and surface structure class according to the Swedish terrain classification (Berg 1991).

Surface structure	Motor manual PCT Slope					Mechanised PCT Slope				
	1	2	3	4	5	1	2	3	4	5
1	10	13				4	6			
2	5	21				6	19	2		
3							3	3		
4		1						6		
5								1		

for terrain classification in forestry (Berg 1991). After PCT, the number of remaining main- and secondary stems, i.e. stems shorter than half the average tree height on the plot, was counted in the four parts of the plot, and all visible damage to the remaining main stems was registered. A stem was recorded as damaged when sapwood could be seen, regardless of wound size. The cause of damage was separated in four classes after mechanised PCT, contact with cutting head, boom contact, contact with wheels and chassis, and unknown reason. For motor manual PCT cause of damage was separated in two classes, damage by the saw blade and other reasons. For each plot, mean height and mean diameter at breast height were calculated as the arithmetic mean of the 40 sample trees. Thereafter, the h/d quota for each plot was calculated as the mean height divided by the mean diameter at breast height.

The two methods of PCT studied were: 1) Motor manual PCT with a conventional brush saw (Husqvarna 252RX). The two workers studied in the motor manual PCT were trained and experienced, both had worked professionally with brush saws for more than 20 years. 2) Mechanised PCT using a winding machine (Vimek 404R). The operator of the machine was, at the time of the study, the most experienced operator of that machine available, having used it for approximately 300 hours. In both treatments the workers were instructed to leave 2200 main stems ha^{-1} after PCT and to avoid damage to the main stems as far as possible. The study was done as a comparative time study with snap back timing (Bergstrand 1987), under daylight conditions in August 2002. Time consumption was recorded in seconds using a stopwatch. For both methods total effective time and delay time was measured. For the mechanical PCT, total effective time was divided into "cleaning" and "moving". "Moving" was recorded when the wheels of the machine were in movement and "cleaning" was the rest of the time recorded. Recording of time began when any part of the tool or operator entered the plot and stopped when the last tree were cut. In mechanised PCT, the number of stopping places for the machine in the plot was recorded. Although delays were recorded, they were excluded from the analyses.

Analysis of covariance (ANCOVA) was carried out, using the univariate procedure in SPSS for windows (release 11.0.0), to detect treatment effects in effective PCT-time per plot (T). In the model covariates were used when they were considered logical and independent from other covariates. Thus, it was not possible to use both mean height and mean diameter at breast height as covariates at the same time. As on some plots there were trees that not had reached breast height, it was decided to use mean height and not mean diameter as covariate. Prior to the analyses two outliers were removed from the dataset. Results of the statistical analyses were considered significant if $p < 0.05$. Three sets of analyses were done:

1) Motor manual PCT and mechanised PCT was compared in an ANCOVA with method (M), slope class (L) and surface structure class (Y) as factors and trees per ha (N), mean height (H) and h/d quota (Q) as covariates using the model

$$T = \mu + \alpha_i^{(M)} + \alpha_j^{(L)} + \alpha_k^{(Y)} + \alpha_{ij}^{(M\times L)} + \alpha_{ik}^{(M\times Y)} + \alpha_{jk}^{(L\times Y)} + \alpha_{ijk}^{(M\times Y\times L)} + \beta_1 N + \beta_2 H + \beta_3 Q + \varepsilon_{ijk}$$

where μ = overall mean, α = fixed effect, $\beta_1, \beta_2, \beta_3$ are constants, ε = random error.

2) The effects of terrain and stand variables on mechanised PCT were analysed using an ANCOVA with slope class and surface structure class as factors and trees per ha, mean height and h/d quota as covariates using the model:

$$T = \mu + \alpha_i^{(L)} + \alpha_j^{(Y)} + \alpha_{ij}^{(L\times Y)} + \beta_1 N + \beta_2 H + \beta_3 Q + \varepsilon_{ij}$$

3) The two workers in the motor manual plots were compared in an ANCOVA with worker (W), slope class and surface structure class as factors and trees per ha, mean height and h/d quota as covariates using the model:

$$T = \mu + \alpha_i^{(W)} + \alpha_j^{(L)} + \alpha_k^{(Y)} + \alpha_{ij}^{(W\times L)} + \alpha_{ik}^{(W\times Y)} + \alpha_{jk}^{(L\times Y)} + \alpha_{ijk}^{(W\times Y\times L)} + \beta_1 N + \beta_2 H + \beta_3 Q + \varepsilon_{ijk}$$

Treatment means were compared with t-test assuming equal variances as a post hoc test to the ANCOVA. In all three cases, in a second step insignificant factors and factors not possible to use for predictions were removed in order to create a reduced model for predictive purposes. Based on the results from previous studies the following model for prediction of time consumption for motor manual PCT, similar to the one used by Lidberg and Svensson (1971), was tested:

$$T = \mu + \alpha_j^{(L)} + \beta_1 NH + \beta_2 Q + \varepsilon_{ijk}$$

3 Results

Motor manual PCT were 0.74 hours ha^{-1} faster than mechanised PCT ($p = 0.006$), all covariates were significant (Table 2), and adjusted R Square for the model was 0.639. Pre-commercial thinning of the average stand (Average height 3.69 m, 10 816 stems ha^{-1} prior to PCT), thus took 5.80 hours ha^{-1} and 5.06 hours ha^{-1} using the mechanised and motor manual method, respectively. After removal of insignificant variables and of the interaction between slope and surface structure, the reduced model became:

$$T = -3.074 + 0.000148n + 0.780h + 0.0431q - 0.969R \tag{1}$$

where T is total time consumption (hours ha^{-1}), n is number of trees per ha, h is the average height of trees (m), q is the quota between height and diameter (m m^{-1}) and R is a dummy variable that gets the value 1 for motor manual and 0 for

Table 2. ANCOVA table for comparison of total time consumption between methods of PCT (motor manual and mechanised PCT).

Source	Type III SS	df	MS	F	Sig.
Corrected model	389955	14	27854	13.3	0.000
Intercept	18601	1	18601	8.9	0.004
Number of stems	67095	1	67095	32.0	0.000
Average height	30977	1	30977	14.8	0.000
Height / Diameter ratio	58997	1	58997	28.1	0.000
Method	46660	1	46660	22.2	0.000
Surface structure	2373	3	791	0.38	0.770
Slope	6591	2	3295	1.6	0.214
Method × Surface structure	3961	1	3961	1.9	0.173
Method × Slope	5416	1	5416	2.6	0.112
Surface structure × Slope	20174	2	10087	4.8	0.011
Method × Surface structure × Slope	8	1	8	0.004	0.951
Error	174134.486	83	2098.006		
Total	6530134.000	98			
Corrected total	564089.102	97			

Table 3. ANCOVA for total time consumption for mechanised PCT.

Source	Type III SS	df	MS	F	Sig.
Corrected model	157241	10	15724	5.1	0.000
Intercept	4715	1	4715	1.5	0.223
Number of stems	21124	1	21124	6.9	0.013
Average height	14325	1	14325	4.7	0.037
Height/Diameter ratio	19544	1	19544	6.4	0.016
Surface structure	453	3	151	0.05	0.985
Slope	6987	2	3493	1.1	0.332
Surface structure × Slope	16693	2	8346	2.7	0.079
Error	116944	38	3077		
Total	3732191	49			
Corrected total	274185	48			

Table 4. ANCOVA for total time consumption for motor manual pre-commercial thinning.

Source	Type III SS	df	MS	F	Sig.
Corrected model	211739	10	21174	18.7	0.000
Intercept	15132	1	15132	13.3	0.001
Number of stems	47311	1	47311	41.7	0.000
Average height	15388	1	15388	13.6	0.001
Height/Diameter ratio	36844	1	36844	32.5	0.000
Worker	6123	1	6123	5.4	0.026
Surface structure	2123	1	2123	1.9	0.179
Slope	5958	1	5958	5.3	0.028
Worker × Surface structure	1094	1	1094	0.96	0.332
Worker × Slope	22	1	22	0.02	0.891
Surface structure × Slope	1516	1	1516	1.3	0.255
Worker × Surface structure × Slope	1343	1	1343	1.2	0.283
Error	43091	38	1134		
Total	2797943	49			
Corrected total	254829	48			

mechanised PCT. Adjusted R square was 0.596. The interaction between slope and surface structure was removed, as it was highly dependant on a few observations.

After mechanised PCT an average of 2475 main stems ha^{-1} and 565 secondary stems ha^{-1} was left. Motor manual PCT left an average of 2805 main stems ha^{-1} and 548 secondary stems ha^{-1}. On average 1.3% and 2.1% of the main stems were damaged by the mechanised and motor manual PCT, respectively. Damage after mechanised PCT were caused by the cutting head in 47% of the cases, the boom in 11% of the cases, the wheels and chassis in 16% of the cases, and by unknown reasons in 26% of the cases. After motor manual PCT all damage were caused by the saw blade.

The Vimek machine was not hindered by slope or surface structure (Table 2). The machine spent 84.6% of the time on cleaning and 15.6% on moving. Adjusted R square was 0.461 for the model in Table 3. As only the covariates were significant the reduced model gave the regression:

$$T = -3.019 + 0.000123n + 0.956h + 0.0394q \qquad (2)$$

Adjusted R square for the reduced model was 0.453.

For motor manual PCT an increase in slope from class 1 to class 2 increased time consumption by 0.64 hours ha^{-1} ($p = 0.028$) and one worker was 0.66 hours ha^{-1} faster than the other ($p = 0.026$). All covariates were significant and no interaction effects among factors could be found (Table 4). Adjusted R square was 0.786 for the model. After removal of insignificant variables and of the effect of worker, the reduced model became:

$$T = -4.830 + 0.000186n + 0.630h + 0.0466q + 0.811L \tag{3}$$

where L is a dummy variable that gets the value 0 for slope class 1, and 1 for slope class 2. Adjusted R square was 0.765. The effect of worker was removed, as it is not of interest for more general estimations of time consumption for PCT.

An alternate model for estimation of motor manual PCT time was:

$$T = -2.015 + 0.000056nh + 0.414q + 0.0693L \tag{4}$$

This model had an adjusted R square of 0.797 and all parameters were significant ($p < 0.015$).

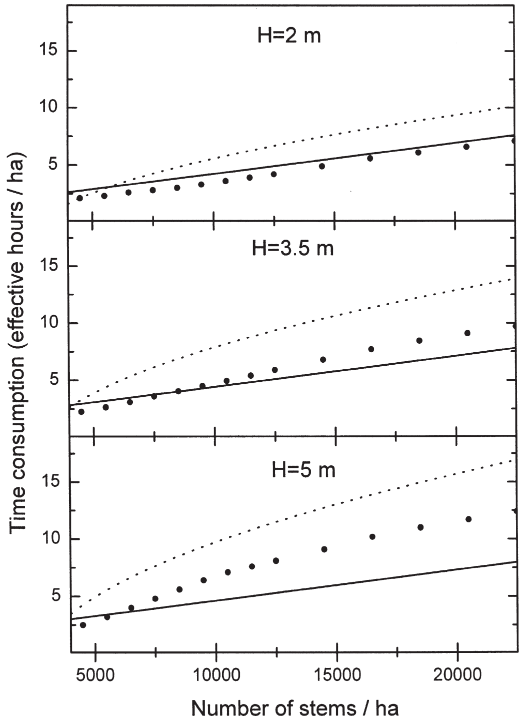

Fig. 3. Time consumption ha^{-1} for motor manual PCT in the present study (Eq. 3, solid line) compared to two earlier studies, Lidberg and Svensson (1971) (dashed line) and Bergstrand et al. (1986) (dots), at three different stand mean heights. All values calculated under comparable conditions and as effective work time.

4 Discussion

Instructions from the landowner, and from other landowners in the area, recommend a remaining stand density of 2200 main stems ha^{-1} after PCT in stands with the site index (T20) of the stand studied (Karlsson et al. 1997, Bäcke and Liedholm 2000). Even though secondary stems are not included in these figures, stand densities after both motor manual and mechanised PCT were too high but would probably be considered acceptable by the landowner. The reason for the somewhat lower number of remaining main stems after mechanised PCT may partly be caused by a closer adherence to the instructions by the machine operator and partly by the fact that visibility increases with decreasing stand density, thus making machine operations easier.

Effective time consumption ha^{-1} for motor manual PCT is lower in this study than in studies from the seventies and eighties (Lidberg and Svensson 1971, Bergstrand et al. 1986) when the same number of stems are cut, and the difference increases with increasing stand mean height (Fig. 3). For a stand with a mean height of 2 m no difference could be noticed between the present study and the results from Bergstrand et al. (1986). One reason for the increased efficiency in motor manual PCT is the continuous development of the brush saw that has been ongoing since the fifties. The main differences between the brush saws used in earlier studies and the present study are lower weight, more ergonomically adapted harnesses, and improved saw blades. As only two workers were studied and the variation in time consumption between workers was large, but quite normal (cf. Lidberg and Svensson 1971, Bergstrand et al. 1986), it is not possible to make an estimate of the decrease in time consumption compared to older studies. However, the existence of a decrease in dense and tall stands is supported by the fact that the difference increases with increasing stand height and stand density, and that the time consumptions decrease from the oldest study to the present one.

The three time consumption functions for motor manual PCT made in this study are similar but Eqs. 3 and 4 are somewhat more sensitive to increases in stand density than Eq. 1. However, caution is needed when doing such comparisons as the h/d quota is not constant when stem density or height is changed. In the comparison in Fig. 3 predicted h/d quotas based on the study material were used when comparing time consumption equations. Eq. 4 was included because it was considered logical that the effect of stand height on time consumption would increase with stand density and vice versa (cf. Lidberg and Svensson 1971, Bergstrand et al. 1986). However, analyses with this type of model did not explain much when analysing the whole material. As almost no spruce occurred in the studied plots the functions presented should be used carefully for PCT in spruce stands since it is known that time consumption for PCT increases as the share of spruce increases (Lidberg and Svensson 1971, Bergstrand et al. 1986).

Average time consumption for mechanised PCT was generally higher than for motor manual PCT, and the difference was constant according to the ANCOVA in Table 1. However, this is partly explained by the fact that on average 313 more stems (4.2%) were removed per ha in mechanised PCT than in motor manual PCT, and partly by the fact that the machine operator concentrated on avoiding damage to the remaining trees. Our suspicion that increased stem density and increased stand height would favour mechanised PCT could not be verified in the study. Logically, increased height induces increased diameter of the stem and that should favour mechanised PCT since it is more tolerant to high diameters than motor manual PCT (Ligné et al. in press). However, there might be other factors dependent of height that affects time consumption for mechanised PCT. One such factor is the visibility, which decreased for the machine operator when the stand reached an average height of 4–5 meters (cf. Freij 1991).

In addition to the traditional influencing factors, height and stem density, the h/d quota turned out to be an important factor explaining the time consumption for PCT. It was highly significant in all models and increased the adjusted R-square for the models with 7 to 18 percentage units. Although the h/d quota turned out to be positively correlated with stem density and negatively correlated with average height combinations of these two variables could not replace the h/d quota in the models.

In earlier studies mechanised PCT has caused more damage to main stems than found in this study, and the fact that it caused less damage than motor manual PCT contradicts what was initially believed. The levels of damage caused by the motor manual PCT was in accordance with earlier studies (Petré 1984, Ligné et al. in press) but the levels of damage caused by the mechanised PCT was lower than in earlier studies of mechanised equipment (Petré 1984, Wästerlund 1988, 1990, Andersson and Mattsson 1993). Earlier PCT-machines often had cutting devices with rotating, flexible flails (Freij 1991, Glöde and Bergkvist 2003), resulting in some damage to main stems from thrown cutting debris (Wästerlund 1990). This problem, as well as the earlier rigorous safety distances (200 metres), should be eliminated with the new shear type felling head. Furthermore, the possibility to use both articulated- and single axle steering makes the Vimek machine more versatile and flexible than earlier types of winding machines, resulting in somewhat lower damage from wheels and chassis.

The cost for PCT depends on the cost and the productivity per scheduled hour for the two methods. This study showed that the productivity per effective hour was higher for the motor manual method than for the mechanised. Due to the small plots it was not possible to present any relations between effective and scheduled work time, according to experience 65 to 75% of the scheduled time is effective work time in motor manual PCT (Prognosunderlag motormanuell… 1991). Utilisation of the PCT machine should be somewhere in between the utilisation of forwarder and a harvester, as it is technically more complex than a forwarder but less complex than a Harvester. A harvester is effectively used 67% and a forwarder 83% of the scheduled time according to Kuitto et al. (1994). Thus it is probable that the share of effective time per scheduled hour is at least as high for the PCT machine as for motor manual work. Both from a work time and a productivity perspective, machine work should be less affected by adverse weather conditions than motor manual work. Mechanised PCT cost twice as much per scheduled hour as motor manual PCT due to higher investment and operational costs (Ligné 2004). The present study thus indicates that mechanised PCT cost approximately twice as much per ha as motor manual PCT, since it seems unlikely that the higher cost per scheduled hour and lower productivity per effective hour for mechanised PCT should be compensated by an increased amount of effective time per hour. This cost difference is comparable to the 87 to 102% higher costs for mechanised PCT reported by Heikkilä (2004).

In the present study only one operator and one work method was studied for the selective mechanised PCT. At the time of study the operator had used the prototype for 300 h and was considered as the most experienced operator thereof. However it is not possible to guarantee that he had fully learnt to use the machine in the most efficient way. For harvesting, it is known that the variation in time consumption per tree between operators is large, up to ca. ±40% of the mean time consumption when thinning (Sirén 2001). It is notable that the difference in time consumption between mechanised and motor manual PCT in this study is comparable to the difference between the two motor manual workers. Although the operator was comfortable with and believed in the work method he used, no tests had been done to ascertain that it was the best method to use. In studies of other machines differences in work methods has influenced productivity with up to 10% (Andersson and Eliasson 2004). As a number of Vimek PCT machines have been built and sold to contractors after the study it is probable that more than one work method is used today. Further studies of the Vimek machine are needed to evaluate work methods in order to find an efficient work method and a number of operators should be included in that study in order to describe the influence of the operator on machine productivity.

In earlier studies a combination of motor manual and mechanised PCT has been preferable from both a cost and a quality perspective in most stands (Freij 1991). From a cost perspective there is probably an advantage to combine schematic and selective PCT (cf. Glöde and Bergkvist 2003, St-Amour 2004), where the schematic treatment is mechanised and the selective either mechanised or motor manual, although there might be concerns about quality and growth effects in main stems after schematic PCT.

5 Conclusions

Efficiency in motor manual PCT has increased compared to older studies. When analysing time consumption for PCT, in addition to height and stand density, the height diameter quota turned out to be an important influencing factor. Motor manual PCT was more time effective than mechanised PCT, and thereby also even more cost-effective. However, the potential for technical and methodological development of mechanised PCT is probably larger than for motor manual PCT.

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