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A pilot study of Continuous Cover Forestry in boreal forests: Decreasing the harvest intensity during selection cutting increases piece size, which in turn increases harvester productivity

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Abstract: While even-aged forestry is the dominating forest management system in Sweden, there is an increasing interest in Continuous Cover Forestry. Consequently, the conversion of even-aged stands into uneven-aged ones using e.g. selection cutting can be expected to become more common in Sweden. However, there are no up-to-date studies available on harvester productivity during selection cutting under Nordic conditions. Studying harvest intensity during selection cutting is of interest because lighter harvest intensities lead to higher volume growth and better-preserved forest ambience than heavier intensities. The objective of this study was to examine the effect of harvest intensity on harvester productivity during selection cutting. The field study entailed harvesting either 14%, 28% or 48% of a mature stand's basal area. Harvester productivity was mainly explained by piece size (stem volume), while other factors, including harvest intensity, had only minor effects. This reality means that during selection cutting (thinning from above), piece size increases with decreasing harvest intensity, which in turn increases harvester productivity. Moreover, we observed a mild tendency that operators could select the stems' felling directions and order more freely when fewer trees are harvested. This amelioration increases productivity additionally during lighter harvesting intensities.

Keywords: automatic time study; cut-to-length logging; multiple-use forestry; partial cutting; single-tree selection; thinning from above

Even-aged forestry (EAF) and continuous cover forestry (CCF). EAF is the dominating forest management system in Nordic forestry (Kuuluvainen et al. 2012). In EAF, a stand is generally managed as a single age class throughout the whole rotation. During a rotation, the stand is thinned (generally from below) once or a few times. Finally, the stand is clearcut, and the ground is reforested. According to Lundqvist (2017) and Hynynen et al. (2019), EAF provides higher volume growth in boreal forests than CCF does. However, EAF decreases biodiversity (Ekholm et al. 2022), increases

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nitrogen leaching, and has an unfavourable esthetical impact on the landscape (Peura et al. 2018).

Because no clearcutting is conducted, CCF provides a continuous forest ambience (Pukkala, von Gadow 2012). According to the Swedish Forest Agency, CCF comprises the following three main methods (Appelqvist et al. 2021): gap-cutting; shelterwood; and selection cutting (also termed single-tree selection or partial cutting). In selection cutting, the oldest age classes, and hence typically the largest trees, are harvested, and the younger age classes gradually replace the previously harvested trees (Kuuluvainen et al. 2012).

Knowledge gap. Because of clearcutting, EAF is becoming increasingly unpopular among the public, especially in the Nordic forest industry's main export markets (Puettmann et al. 2015). Consequently, the pressure to rethink forest management practices in Nordic forestry is increasing. Converting EAF stands into more publicly accepted CCF stands is of interest in many forests of the Nordic countries. There are up-to-date time studies on shelterwood logging and patch cutting from northern European conditions (Grönlund, Eliasson 2019; Eliasson et al. 2021), but the most relevant studies on thinning from above (Lageson 1996; Eliasson 1998) and selection cutting (Suadicani, Fjeld 2001) are already decades old. There are newer time studies on selection cutting from central Europe (Mederski 2006; Mederski et al. 2016). However, there are significant differences in practices and conditions when comparing central European and Nordic forestry. Therefore, the results of central European studies can be applied in the Nordic context only with caution.

Objectives. To meet the growing interest in CCF, more knowledge is needed, especially regarding selection cutting. Hence, the objective of this study was to examine the effect of harvest intensity on a large harvester's productivity during selection cutting.

MATERIAL AND METHODS

Study setup. The field study was carried out in central Sweden in the spring of 2021 using a large 23-ton Ponsse Scorpion harvester (Figure 1A). The harvester was equipped with a rotating and levelling cabin, a C50 crane (reach 11 m), and an H6 harvester head.

Three homogeneous study plots were demarcated in a mature conifer-dominated stand (Figure 1B, Table 1). Each harvest intensity was randomly assigned to one of the study plots. The size of each study plot was 30 m × 80 m. The plots' terrain conditions were classified according to the Swedish Terrain Classification System (Berg 1992) as follows: bearing capacity (ground condition) 2; surface structure (ground roughness) 2; and inclination (slope) 1. Two circular sample plots (r = 9.78 m) were set up in each study plot and inventoried before and after harvesting according to the instructions in Högberg (2019).

The harvester operator had > 10 years of experience with harvester work in selection cutting. In accordance with the standard Nordic practice, the operator independently selected which trees were

Figure 1. (A) The Ponsse Scorpion 23 tonne harvester at the start of the field time study; (B) part of the study stand; the dominant and codominant trees (overstory) were mainly pine (*Pinus sylvestris*), while the intermediate and suppressed trees (understory) were mainly spruce (*Picea abies*) and some birch (*Betula spp*) (the stand was circa 90 years old, and it had been thinned once from below during the 1990s)

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Table 1. Descriptive statistics regarding the outcome of the field study – initial conditions in the plots were similar but the harvest intensities resulted in different outcomes

Harvest intensity	Average per harvested stem			Mean displacement (m)[a]	Pine proportion of the harvested trees (%)[b]	*N*
	volume (m^3)	number of logs	number of assortments			
Light	0.867	5.4	2.7	5.5	64.7	17
Medium	0.807	5.1	2.6	4.9	63.6	33
Heavy	0.500	4.8	2.7	3.4	76.9	65
Data pooled	0.642	5.0	2.7	4.2	71.3	115

[a]arithmetic mean displacement between the subsequent machine positions; [b]the rest was spruce; *N* – final number of stems included in the dataset

to be cut. The operator was instructed to harvest either 15%, 30%, or 45% of the basal area depending on the applied harvest intensity (also termed harvest strength or cutting/thinning intensity). The post-harvest inventory of the circular sample plots showed that the operator followed the instructions precisely. The actualised harvest intensities were 14%, 28% and 48%, respectively. Hereafter, we name these harvest intensities as "light" (14%), "medium" (28%) and "heavy" (48%).

Similar to Strandgard et al. (2013), we based our time study on the data extracted from StanForD files with a stem (i.e. tree) as the unit of observation. Thus, the time consumption for a stem commenced simultaneously with the felling cut of that stem, and the time stopped simultaneously when the next felling cut commenced. In general, both in Strandgard et al. (2013) and in our study, time consumption for stem_n equalled the interval from time label_n to time label_{n+1}.

However, unlike the stem files used in Strandgard et al. (2013), which lacked coordinates of the machine positions, we used a newer communication standard named harvested production (hpr) files in our study. When using hpr-files, harvesters record the point of time and their own geographical position during each felling cut (Arlinger et al. 2019). These time-labelled machine positions are then automatically saved in the hpr-file. This feature enabled us to determine the displacement between the subsequent machine positions with the help of the Pythagorean theorem. In general, if stem_n was cut at machine position (x_n, y_n) and stem_{n+1} correspondingly at position (x_{n+1}, y_{n+1}), then the displacement from (x_n, y_n) to (x_{n+1}, y_{n+1}) equalled

$$\sqrt{\left(x_{n+1} - x_n\right)^2 + \left(y_{n+1} - y_n\right)^2}\ .$$

Hence, driving events, i.e. displacements between subsequent machine positions, were coupled to an initial stem rather than a later one. Because several stems were typically harvested at each machine position, most stems were not affected by a driving event and a displacement of 0 m was recorded for these stems. Displacement observations were treated as continuous variables (see below).

And lastly, because stem volumes (or piece size; Visser, Spinelli 2012) were also known, we could calculate time consumption ($s \cdot m^{-3}$) for each stem. Interruptions were recorded manually during the field study using a stopwatch, which enabled a clean dataset free from interruptions. This circumstance provided us with productive machine (PM) time, including only effective work time (IUFRO 1995). Volume measurements did not include the bark (i.e. volumes were solid under bark).

In addition, the following variables were retrieved stem-wise from the hpr-files for statistical modelling: tree species, number of assortments, and number of logs (Table 1). These variables are readily available in the hpr-files without requiring any further data processing. The last stem of each plot was not included in the dataset because the it is missing its ending point (because the label of the subsequent felling cut does not exist). No other data filtering was done.

Analysis of covariance (ANCOVA). Our study had only one dependent variable, time consumption ($s \cdot m^{-3}$), and two categorical variables, harvest intensity and tree species. We hypothesised that harvest intensity *per se* has no direct effect on the time consumption *ceteris paribus*. Instead, we assumed that the harvest intensity affects the time consumption indirectly because stem volume varies depending on the harvest intensity. Therefore,

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in addition to the aforementioned displacement, we also entered into the statistical model stem volume, number of logs per stem, and number of assortments per stem as continuous variables. General Linear Model was used to analyse the ANCOVA model. Pairwise differences (post-hoc) were analysed using the Tukey-Kramer method. The significance level was set to 5%. ANCOVA assumptions were checked according to Barrett (2011) and Johnson (2016). SAS (Version 9.4, 2020) was used for all statistical analyses.

RESULTS AND DISCUSSION

ANCOVA and linear regression. The number of assortments per stem and number of logs per stem were excluded from the final model because they neither had a significant effect on time consumption nor improved residual behaviour. Time consumption ($s \cdot m^{-3}$) decreased with increasing stem volume, decreasing harvest intensity, and decreasing displacement between machine positions. The processing of spruce, *Picea abies*, took more time than the processing of pine, *Pinus sylvestris* (Table 2).

Post-hoc analysis. The harvest intensities medium and heavy did not differ significantly from each other, *ceteris paribus* (P = 0.7788, Table 3). However, the time consumption was significantly lower (from 21.0 $s \cdot m^{-3}$ to 25.2 $s \cdot m^{-3}$) during the light harvest intensity compared to the other two harvest intensities, *ceteris paribus* ($0.0105 \le P \le 0.0256$, Table 3). Thus, the ANCOVA did not entirely support our hypothesis that harvest intensity does not have a significant direct effect on the time consumption when stem volume and other factors are kept equal between the harvest intensities. One reason for that result could be the following: with the lightest harvest intensity, the operator could freely select the stems' felling directions and order. Contrariwise, with heavier intensities, the operator must consider in advance which order and direction trees are to be felled. Furthermore, heavier harvest intensities limit how freely the piles can be placed along the strip roads. Hence, in general, lighter harvest intensities probably facilitate faster harvester crane work.

Pooling the data. Despite the fact that the ANCOVA did not thoroughly support our hypothesis, our theory remains valid in practice. The great majority (86%) of the total variation in time consumption was explained solely by stem volume, while other factors (displacement between the machine positions, tree species, and harvest intensity) had only minor effects (Table 2, detailed data not shown). Thus, time consumption could be modelled solely based on stem volume (Figure 2). A closer look at Figure 2 shows that initially, time consumption decreased rapidly with increasing stem volume but started to plateau beyond circa 0.5 m^3. Only one of 17 stems (i.e. 5.9%) processed during the light harvest intensity was smaller than 0.5 m^3. On the other hand, six of 33 stems (i.e. 18.2%) processed during the medium harvest intensity and 35 of 65 stems (i.e. 53.8%) during the heavy harvest intensity were smaller than 0.5 m^3.

Limitations of the study and future research. Although the small dataset and the fact that our study included only one operator limit the generalizability of our study, it produced logical results with well-controlled error. Our study can at least

Table 2. Analysis of covariance (ANCOVA); dependent variable: productive time consumption ($s \cdot m^{-3}$), the unit of observation is stem, N = 115 (see Table 1), R^2 = 0.890

ANCOVA			Linear regression analysis				
Parameter	F	P-value	parameter	estimate	SE	t-value	P-value
Harvest intensity	4.66	0.0114	light	–20.992	7.954	–2.64	0.0095
			medium	4.216	6.249	0.67	0.5014
			heavy	0	–	–	–
Stem volume^{-1} (m^3)	857.11	< 0.0001	stem volume^{-1}	17.677	0.604	29.28	< 0.0001
Displacement (m)	12.1	0.0007	displacement	3.139	0.902	3.48	0.0007
Tree species	7.43	0.0075	spruce	16.007	5.870	2.73	0.0075
			pine	0	–	–	–
Intercept	–	–	intercept	42.168	5.164	8.17	< 0.0001

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Table 3. Time consumption depending on the harvesting intensity with other factors kept constant: stem volume = 0.41 m^3, displacement between machine positions = 4.16 m, tree species = pine

Intensity	Time consumption ($s \cdot m^{-3}$)	*N*
Light	77.6^{A}	17
Medium	102.8^{B}	33
Heavy	98.6^{B}	65

^{A,B}Different superscripted letters indicate significant differences ($P \leq 0.05$, Tukey-Kramer method)

be seen as a pilot study confirming a relationship well-known among harvester operators when thinning from above (i.e. that lighter harvest intensities lead to larger piece sizes and thus higher harvester productivities), which is poorly described in the literature. However, in future studies, standard hpr-data should preferably be complemented with StanForD extension variables. These extensions enable the recording of PM time without complementary manual timing and the detection of distinct work elements. Indeed, hpr-files are a clear upgrade from the old stem-files [cf. Table 2 and Strandgard et al. (2013)]. Moreover, these future studies should be based on larger datasets comprising several stands and operators. This supplementation would, in turn, enable meaningful costing and profitability analysis of selection cutting in boreal forestry.

CONCLUSION

With decreasing harvest intensity, the volumes of harvested stems (piece sizes) increase, which in turn increases harvester productivity during selection cutting (thinning from above) in mature stands. Moreover, with lighter harvest intensities, operators can more freely select the stems' felling directions and felling order and the log piles' placement along the strip roads. Hence, in general, lighter harvest intensities probably facilitate faster crane work and, thereby, higher harvester productivity.

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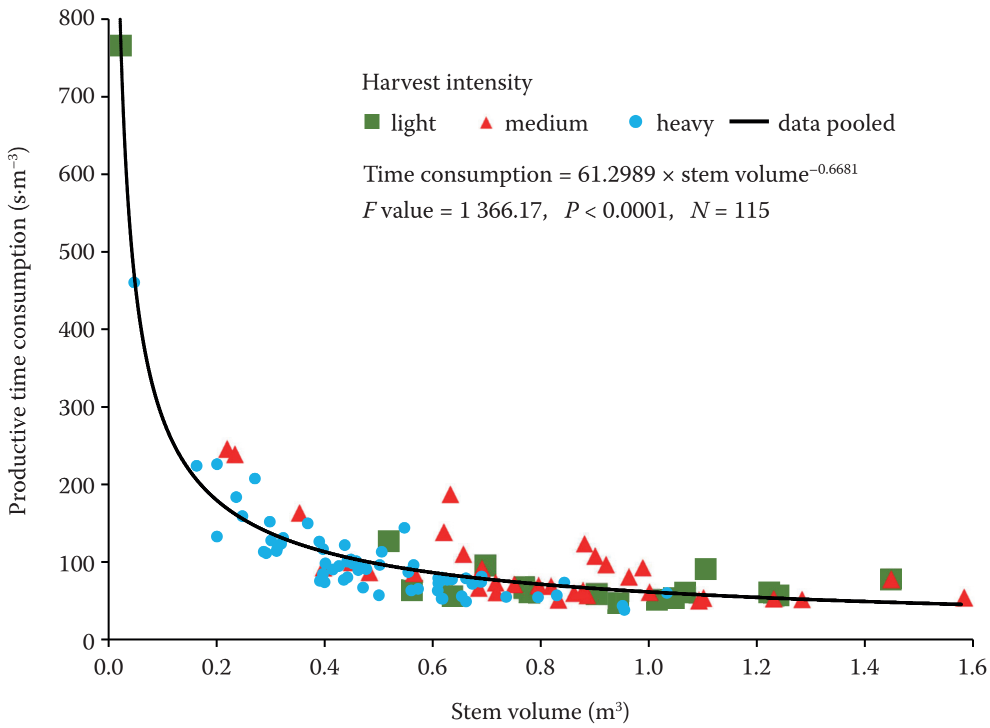

Figure 2. Nonlinear regression analysis on the pooled data: productive time consumption ($s \cdot m^{-3}$) as a function of stem volume (m^3)

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