https://doi.org/10.17221/44/2023-JFS

A pilot study of continuous cover forestry in boreal forests: Do remaining trees affect forwarder productivity?

Jussi Manner[1], Back Tomas Ersson[2]*

[1]*Skogforsk, Uppsala, Sweden*

[2]*School of Forest Management, Swedish University of Agricultural Sciences, Skinnskatteberg, Sweden*

**Corresponding author: jussi.manner@skogforsk.se*

Citation: Manner J., Ersson B.T. (2023): A pilot study of continuous cover forestry in boreal forests: Do remaining trees affect forwarder productivity? J. For. Sci., 69: 317–323.

Abstract: According to the literature, forwarding productivity depends chiefly on log concentration, the number of assortments, mean log volume, load-size, slope, and extraction distance. However, there is not much scientific knowledge available on forwarding in continuous cover forestry (CCF) in boreal forests, nor whether the presence of remaining trees actually affects forwarding productivity. Thus, the objective of our study was to isolate the effect of remaining trees (i.e. stand density) on forwarding productivity during CCF, specifically selection cutting. The results showed that productivity was explained mainly by the log concentration, while other factors had at most minor effects. Most importantly, stand density did not significantly affect forwarding productivity, *ceteris paribus*. Thus, we conclude that remaining trees do not affect forwarding productivity in boreal forests. Although the study results from this CCF operation must only be cautiously applied to even-aged forestry, our results raise a general question: do we need separate productivity models for thinning and clearcut operations in boreal forests if remaining trees (stand density) do not affect forwarding productivity? Because of the small dataset, we consider our paper to be a pilot study whose findings need to be verified by studies based on larger datasets including several operators and stands.

Keywords: cut-to-length logging; time study; forest operation; partial cutting; single-tree selection; extraction

According to modern forwarding literature, log concentration, expressed as e.g. roundwood volume m^3 per 100 m of strip-road [$m^3 \cdot (100\ m)^{-1}$], is clearly the most important factor influencing forwarding productivity (Grönlund, Eliasson 2019; Hildt et al. 2020). Moreover, assortment type, the number of assortments, mean log volume, mean stem volume, number of logs per load, load-size, ground slope (if steep), and extraction distance have also been found to affect forwarding productivity (Nurminen et al. 2006; Eriksson, Lindroos 2014; Strandgard et al. 2017; Cadei et al. 2020; Hildt et al. 2020). The unit of observation in forwarding studies is typically a load (Strandgard et al. 2017; Cadei et al. 2020; Hildt et al. 2020), but it can also be a stand (Eriksson, Lindroos 2014).

Usually, forwarding productivity during thinning and clearcutting is modelled separately, both in boreal forests and beyond (Nurminen et al. 2006; Eriksson, Lindroos 2014; Proto et al. 2018). That said, unlike harvester work during typical boreal thinning operations, forwarding does not require tree-selection decisions from the operator. Thus, given that the above-mentioned factors affecting

Supported by Svea Janssons Skogsfond.

forwarding productivity are kept equal, the presence of remaining trees during thinning is the main difference between thinning and clearcutting.

Objectives. Today, there is not much scientific knowledge available on whether the remaining trees affect forwarding productivity, *ceteris paribus* (other things equal). This shortcoming might be because of the difficulty in isolating the effect of remaining trees during ordinary boreal logging operations. However, isolating the effect of remaining trees on forwarding productivity might be easier during selection cutting, which indeed is the novelty and objective of our study. To address this knowledge gap, we analysed the effect of stand density (i.e. the number of remaining trees) on forwarding productivity during selection cutting in boreal forests. We hypothesized that forwarding productivity decreases with increasing stand density, *ceteris paribus*.

MATERIAL AND METHODS

Study setup. The field study was carried out in central Sweden in spring 2022 using a John Deere 1110G forwarder (load capacity: 12 t, John Deere Forestry, Finland). The forwarder was equipped with a rotating and levelling cabin, a CF7 crane (reach: 8.5 m, Waratah, Finland), and a HSP 035 Duo grapple (grapple area: 0.35 m^2, Hassela Skogsprodukter Aktiebolag, Sweden).

To accommodate the field study, three homogeneous plots were demarcated in a mature conifer-dominated stand (Figure 1). The size of each plot was 1 ha. The demarcated plots were then thinned from above prior to the forwarding operation, and the target number of remaining trees after the thinning was set either to 170 $trees{\cdot}ha^{-1}$ or 340 $trees{\cdot}ha^{-1}$, hereafter named 'Sparse' and 'Dense', respectively. To ensure approximately equal roundwood volume between the treatments and hence approximately equal number of forwarder loads, prior to the harvesting two of the plots were randomly assigned to stand density 'Dense', whereas one plot was assigned to 'Sparse'. According to control measurements, the actualized stand densities after thinning were 182 $trees{\cdot}ha^{-1}$ (Sparse) and 321 $trees{\cdot}ha^{-1}$ (Dense), respectively.

The plots' terrain conditions were classified according to the Swedish Terrain Classification System (Berg 1992) as follows: bearing capacity: 1; ground roughness: 2; slope: 1. The soil type was mesic, sandy-loam till (moraine) with a field layer consisting mainly of *Vaccinium myrtillus*. The pre-harvest growing stock was circa 230 $m^3{\cdot}ha^{-1}$. The overstory of the study stand was relatively sparse because the stand is in a transformation stage; i.e. a previously even-aged stand is gradually being converted into an uneven one. The forwarder operator had nearly 40 years of experience in forwarder work, of which one year was in selection cutting, i.e. thinning from above.

Indata, work elements and time observations. We divided the 'loading stage' into two separate work elements: 'crane work' and 'driving'. Crane work was always the first time interval, and hence the first work element, of a new forwarding cycle. Time intervals for a crane work event commenced as the crane started to move, and the time intervals ended when the crane stopped moving. In this paper 'a crane' comprises the whole boom system, including the grapple. Driving events (i.e. time intervals) between the crane work intervals were defined as driving, given that no crane work occurred simultaneously. Thus, crane work was prioritized over driving, i.e. simultaneous driving and crane work was determined as crane work (Tiernan et al. 2004; Cadei et al. 2020). We did not separate crane work and driving during the unloading stage; there, all work was collectively categorized as 'Unloading'.

All driving between the work elements unloading and the crane work during loading stage was defined as either 'driving empty' or 'driving loaded'. Driving empty and driving loaded were outright excluded from the dataset. Time consumption for these purely driving work elements can be reliably calculated as the relationship between distance driven and speed. Variations in driving speeds and distances have been thoroughly analysed and documented, e.g. in the large follow-up study of Berg et al. (2019).

After each accomplished forwarding cycle (a load), time intervals were summarized work-element-wise. Hence, the unit of observation was a forwarder load. The results are given as productive machine time (PMh). As is customary, we defined PMh as delay-free machine hours (Eriksson, Lindroos 2014), which includes only effective work time. Inactivity longer than 20 s was categorized as pauses (i.e. ineffective time) and excluded from the dataset. If inactivity shorter than 20 s occurred between separate work elements, the inactivity

https://doi.org/10.17221/44/2023-JFS

Figure 1. Forwarding in central Sweden during the field study in the 'Sparse' treatment, i.e. 182 remaining trees·ha^{-1} after the harvesting operation (thinning from above); the overstory was pine (*Pinus sylvestris*) dominated and circa 85 years old, the understory was spruce dominated (*Picea abies*)

Photo: Max Hedlund

in question was incorporated into the initial work element rather than the later one.

All wood volumes in the present study include the bark (solid on bark). Load volumes were approximated based on the forwarder's load-area, the average length of the logs (retrieved plot-wise from the harvester's hpr-file), and a solid volume conversion factor (Biometria 2020). Because total volumes measured by the harvester were available plot-wise via hpr-files, we could compare the sum of the approximated load volumes against the plot-specific total volume. The sums of approximated load volumes differed plot-wise by less than 1 m^3 from the harvester-measured volumes. This indicates that the approximated load volumes were sufficiently accurate.

Analysis of covariance (ANCOVA). When modelling time consumption (min·m^{-3}) during the loading stage, stand density (either 182 trees·ha^{-1} or 321 trees·ha^{-1}) was entered as a categorical variable in the statistical model. Forwarded log concentration, a quotient of load-size (m^3) and loading distance (m), was entered as a continuous variable in the statistical model. Loading distance is the distance driven from the load's first to last loaded pile. Hereafter, forwarded log concentration is simply termed as 'log concentration'. Moreover, we multiplied log concentration with 100 to reduce deci-

https://doi.org/10.17221/44/2023-JFS

mals and provide the variable log concentration per 100 m distance [$m^3 \cdot (100\ m)^{-1}$]. It varied from 2.07 $m^3 \cdot (100\ m)^{-1}$ to 10.26 $m^3 \cdot (100\ m)^{-1}$ during the field study. Loading distances were determined using the forwarders' trip meter readings. Mean log volume, a quotient of load-size (m^3) and the number of logs, was entered as a continuous variable in the statistical model. Mean log volume varied from 0.081 m^3 to 0.283 m^3. The logs were counted after the field study based on photos of the loads (Figure 2).

Unloading was modelled solely based on the mean log volume being a continuous variable. Moreover, the number of assortments in a load was two with two exceptions: one load comprised only a single assortment, and one load comprised three assortments. And because of the uniform conditions at the roadside landing, only minor, practically non-existent, machine repositioning was required during the unloading, irrespective of the number of assortments unloaded (Figure 2). Therefore, including the number of assortments in a load in the analysis was not meaningful.

A general linear model was used to analyse the ANCOVA models. The significance level was set to 5%. ANCOVA assumptions were checked according to Barrett (2011) and Johnson (2016). SAS software (Version 9.4, 2020) was used for all statistical analyses. Prior to the actual statistical analysis, the stand density was also temporarily included in the unloading model to control whether the loads unexpectedly differed between the stand densities. As expected, the loads did not significantly differ between the study plots (P = 0.5015).

Figure 2. The study's roadside landing provided uniform conditions between loads; the operator could easily unload up to three assortments with very minimal machine movements

Photo: Anton Jernberg

https://doi.org/10.17221/44/2023-JFS

RESULTS AND DISCUSSION

ANCOVA, linear regression and post hoc. Dividing the loading stage into crane work and driving did not work out. Large proportions of the driving occurred simultaneously with crane work; and because of the hierarchy applied, we identified this simultaneous work solely as crane work. Consequently, the statistical results were poor especially for driving; meanwhile, thanks to its higher hierarchy, the crane work's statistical results were somewhat better (Table 1).

Combining crane work and driving into a single work element solved the hierarchy-related problem and resulted in relatively good statistical results (Table 1, Loading in total). Loading time, in line with a current literature (Grönlund, Eliasson 2019; Hildt et al. 2020), decreased with increasing log concentration (Table 1; P = 0.012). Moreover, loading time decreased with increasing mean log volume, similarly to Hildt et al. (2020), but in our study, the decrease fell just outside of the set significance level (Table 1; P = 0.098). That said, the inclusion of mean log volume slightly harmonized residual behaviour (no data shown).

Stand density did not have a significant effect on the loading time consumption, *ceteris paribus* (Table 1; P = 0.901). For instance, when entering the study's mean log concentration [4.64 $m^3 \cdot (100\ m)^{-1}$] and mean log volume (0.162 m^3) into the linear regression model, it gives practically equal time consumption irrespective of stand density: 0.94 $min \cdot m^{-3}$ for Sparse, and 0.96 $min \cdot m^{-3}$ for Dense, respectively (Table 1).

Non-linear regression. In addition to combining crane work and driving, the ANCOVA results suggest to us that further simplifications are possible. Because the great majority of the loading time was solely explained by the log concentration (Table 1, Loading in total), we simplified the linear

Table 1. Analysis of covariance (ANCOVA). The dependent variable is effective time ($min \cdot m^{-3}$) per work element; categorical variable is stand density, either Sparse (182 $trees \cdot ha^{-1}$) or Dense (321 $trees \cdot ha^{-1}$); continuous variables are mean log volume (*MLV*, m^3) and log concentration* [*LC*, $m^3 \cdot (100\ m)^{-1}$]; *MLV* varied from 0.081 m^3 to 0.283 m^3, and *LC* from 2.07 $m^3 \cdot (100\ m)^{-1}$ to 10.26 $m^3 \cdot (100\ m)^{-1}$, respectively; these ranges can also be considered as feasible domains for the linear regression models; five loads were forwarded during the stand density Sparse and six during the Dense, respectively; the unit of observation is a load (n = 11)

Dependent variable ($min \cdot m^{-3}$)	ANCOVA		Linear regression analysis					Adjusted R-square
	parameter	F	parameter	estimate	standard error	t-value	P-value	
Crane work during loading stage	stand density	0.19	Dense	0.050	0.115	0.440	0.674	0.647
			Sparse	0.000	–	–	–	
	MLV	1.53	*MLV*	–1.003	0.812	–1.240	0.257	
	LC^{-1}	6.36	LC^{-1}	1.796	0.712	2.520	0.040	
			intercept	0.375	0.256	1.470	0.186	
Driving during loading stage	stand density	0.17	Dense	–0.033	0.080	–0.410	0.695	0.519
			Sparse	0.000	–	–	–	
	MLV	2.05	*MLV*	–0.815	0.569	–1.430	0.195	
	LC^{-1}	4.05	LC^{-1}	1.005	0.500	2.010	0.084	
			intercept	0.261	0.180	1.450	0.190	
Loading in total	stand density	0.02	Dense	0.017	0.135	0.130	0.901	0.774
			Sparse	0.000	–	–	–	
	MLV	3.64	*MLV*	–1.818	0.953	–1.910	0.098	
	LC^{-1}	11.23	LC^{-1}	2.801	0.836	3.350	0.012	
			intercept	0.636	0.301	2.120	0.072	
Unloading			*MLV*	–0.532	0.109	–4.90	0.001	0.697
			intercept	0.360	0.021	17.17	< 0.0001	

*roundwood volume m^3 per 100 m's distance on the strip-road, formula: 100 × load volume (m^3) / loading distance (m)

https://doi.org/10.17221/44/2023-JFS

regression into non-linear regression and modelled loading time solely based on the log concentration (Figure 3A). To summarize, the stand density might seemingly affect forwarding productivity, but in reality, the log concentration is the affecting factor.

Unloading. Time consumption decreased mildly, but statistically significantly, with increasing mean log volume (Table 1, Unloading; $P = 0.001$). Because of equal unloading conditions, the time consumption did not vary meaningfully between the loads, and the time consumption was mainly determined by the intercept.

Trees along the haul trail. Because some parts of pure driving work (i.e. driving empty and driving loaded) typically occur on the strip-road (Hansson et al. 2022), the remaining trees might also affect pure driving. That said, we knowingly excluded pure driving from our study because the major part of this work occurs on the haul trail and even at the landing. Trees standing along the haul trail or at the landing do not meet the criteria of remaining trees because they are not directly linked to the type of logging operation (e.g. thinning, clearcutting, etc.); for instance, a haul trail from a thinning stand might go through a clearcut and *vice versa*. Moreover, it is unlikely that the remaining trees would impact pure driving more than they impact loading work. Furthermore, pure driving comprises a lesser proportion of forwarding time than loading does (Figure 3B). Therefore, moderate variations in pure driving time would have a very mild impact on forwarding productivity anyways.

Recommendations for application of results and further research. Although the novelty of our study was to isolate the effect of remaining trees (i.e. stand density) on forwarding productivity during continuous cover forestry (more accurate selection cutting), the results can also be cautiously used to compare productivity during clearcut and thinning operations. Thus, the results raise a question: Do we really need separate forwarder productivity models for

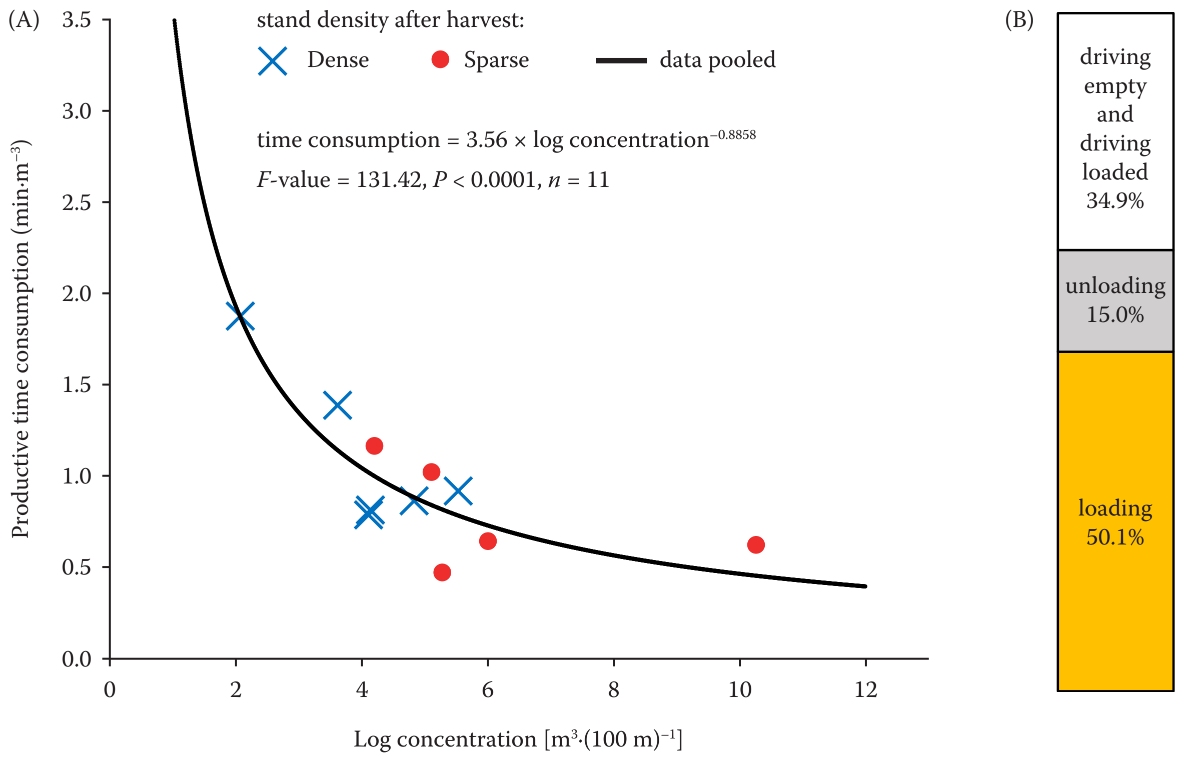

Figure 3. (A) Effective time consumption (min·m^{-3}) for loading (incl. crane work and driving) as a function of log concentration [m^3·(100 m)$^{-1}$] during the study; in the nonlinear regression analysis, we used data pooled across stand density after harvest (Dense: 321 trees·ha^{-1}, and Sparse: 182 trees·ha^{-1}); (B) the distribution of forwarding time consumption during the study; loading time is according to the non-linear regression of Figure 3A at the present study's mean log concentration of 4.64 m^3·(100 m)$^{-1}$; unloading time is according to Table 1 at the present study's mean log volume of 0.162 m^3; driving empty and driving loaded times are calculated based on the medians of the follow-up dataset of Berg et al. (2019): driving empty time = 240 m × (54.8 m·min^{-1})$^{-1}$, and driving loaded time = 189 m × (45.7 m·min^{-1})$^{-1}$; driving empty and driving loaded times are divided by the present study's mean load-size (13.4 m^3) to give a time consumption per m^3

https://doi.org/10.17221/44/2023-JFS

thinning and clearcut operations if remaining trees (stand density) do not affect forwarding productivity?

That said, even the highest stand density in our study was relatively sparse, and consequently the difference between Sparse and Dense was not as drastic as the difference between Nordic thinning and clearcut operations. In fact, the number of remaining trees varies radically when forwarding during even-aged forestry; from dense (first thinning) to practically no trees at all (clearcut). Therefore, our study results from this selection cutting operation must only be cautiously applied to even-aged forestry.

Although there are some international field studies with manually collected datasets that are large and representative (e.g. Hildt et al. 2020), Nordic field studies are typically based on a very small number of loads or only one operator (Nurminen et al. 2006; Manner et al. 2013; Grönlund, Eliasson 2019). Our study is not an exception: our small dataset and the fact that the study included only one operator decrease the representativeness of our study. That said, our field study was well-controlled and produced logical results in line with current literature. Nevertheless, our findings need to be verified by studies based on larger datasets that include several operators and stands. Therefore, we consider our study to be a novel pilot study that raises relevant questions for further investigation.

CONCLUSION

The ANCOVA did not support our hypothesis, which was that forwarding productivity decreases with increasing stand density. Instead, forwarding productivity did not decrease with increasing stand density, i.e. the number of remaining trees did not affect forwarding productivity during selection cutting, *ceteris paribus*. That said, our study was a pilot study, and more research is needed on this topic before definitive conclusions can be made.

Acknowledgement: We graciously thank Max Hedlund and Anton Jernberg for the data gathering.

REFERENCES

Barrett T.J. (2011): Computations using analysis of covariance. Wiley Interdisciplinary Reviews: Computational Statistics, 3: 260–268.

Berg S. (1992): Terrain Classification System for Forestry Work. Stockholm, Forest Operations Institute: 28.

Berg S., Ersson B.T., Manner J. (2019): Distance driven and driving speed when forwarding during final felling in Central Sweden. Journal of Forest Science, 65: 183–194.

Biometria (2020): Measurement of roundwood stacks. Swedish regulations for timber measurement. Version 2020-10-01. Available at: https://www.biometria.se/media/a5xchk3j/measurement-of-roundwood-stacks-2020-10-01.pdf

Cadei A., Mologni O., Röser D., Cavalli R., Grigolato S. (2020): Forwarder productivity in salvage logging operations in difficult terrain. Forests, 11: 341.

Eriksson M., Lindroos O. (2014): Productivity of harvesters and forwarders in CTL operations in northern Sweden based on large follow-up datasets. International Journal of Forest Engineering, 25: 179–200.

Grönlund Ö., Eliasson L. (2019): Birch shelterwood removal – Harvester and forwarder time consumption, damage to understory spruce and net revenues. International Journal of Forest Engineering, 30: 26–34.

Hansson L.J., Forsmark V., Flisberg P., Rönnqvist M., Mörk A., Jönsson P. (2022): A decision support tool for forwarding operations with sequence-dependent loading. Canadian Journal of Forest Research, 52: 1513–1526.

Hildt E., Leszczuk A., Mac Donagh P., Schlichter T. (2020): Time consumption analysis of forwarder activities in thinning. Croatian Journal of Forest Engineering, 41: 13–24.

Johnson T.R. (2016): Violation of the homogeneity of regression slopes assumption in ANCOVA for two-group pre-post designs: Tutorial on a modified Johnson-Neyman procedure. The Quantitative Methods for Psychology, 12: 253–263.

Manner J., Nordfjell T., Lindroos O. (2013): Effects of the number of assortments and log concentration on time consumption for forwarding. Silva Fennica, 47: 1030.

Nurminen T., Korpunen H., Uusitalo J. (2006): Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fennica, 40: 335–363.

Proto A.R., Macrì G., Visser R., Harrill H., Russo D., Zimbalatti G. (2018): Factors affecting forwarder productivity. European Journal of Forest Research, 137: 143–151.

Strandgard M., Mitchell R., Acuna M. (2017): Time consumption and productivity of a forwarder operating on a slope in a cut-to-length harvest system in a *Pinus radiata* D. Don pine plantation. Journal of Forest Science, 63: 324–330.

Tiernan D., Zeleke G., Owende P.M.O., Kanali C.L., Lyons J., Ward S.M. (2004): Effect of working conditions on forwarder productivity in cut-to-length timber harvesting on sensitive forest sites in Ireland. Biosystems Engineering, 87: 167–177.

Received: April 20, 2023
Accepted: May 30, 2023