Sveriges lantbruksuniversitet
Swedish University of Agricultural Sciences

This is an author produced version of a paper published in
Scandinavian Journal of Forest Research.
This paper has been peer-reviewed and is proof-corrected, but does not include the journal pagination.

Citation for the published paper:
Lars Sängstuvall, Dan Bergström, Tomas Lämås & Tomas Nordfjell. (2012) Simulation of harvester productivity in selective and boom-corridor thinning of young forests. *Scandinavian Journal of Forest Research*. Volume: 27, Number: 1, pp 56-73.
http://dx.doi.org/10.1080/02827581.2011.628335.

Simulation of harvester productivity in selective and boom-corridor thinning of young forests

Simulation of harvester productivity

Lars Sängstuvall

Dan Bergström

Tomas Lämås

Tomas Nordfjell

Dept. of Forest Resource Management, SLU
SE-901 83 Umeå, Sweden

Contact: lars.sangstuvall@slu.se
Tel. +46-90-7868201
Fax. +46-90-778116

Abstract

Forest management practices may change in the future, due to increases in the extraction of forest fuel in first thinnings. Simulation models can be used to aid in developing new harvesting systems. We used such an approach to assess the productivity of innovative systems in various thinnings of young stands with wide ranges of mean breast height diameter (1.5 - 15.6 cm), stems per hectare (1 000 - 19 100) and mean height (2.3 - 14.6 m).

The results show that selective multiple-tree-handling increases productivity by 20 – 46% compared to single-tree-handling. If the trees are cut in boom-corridors (narrow 10 m strips between strip roads), productivity increases up to 41%, compared to selective multiple-tree-handling. Moreover, if the trees are felled using area-based felling systems, productivity increases by 33 - 199 %, compared to selective multiple-tree-handling. For any given harvesting intensity , the increases in productivity were highest in the densest stands with small trees.

The results were used to derive time consumption functions. Comparisons with time study results suggest that our simulation model successfully mimicked productivity in real-life forest operations, hence the model and derived functions should be useful for cost calculations and evaluating forest management scenarios in diverse stands.

Keywords

Bioenergy, forest fuel, geometric thinning, multiple-tree-handling, roundwood, single-tree-handling, tree sections, time consumption, whole-tree

Introduction

Various types and intensities of thinnings can be applied in practical forestry, depending on the initial stand characteristics and management objectives (cf. Lageson, 1997). However, thinning operations in young forests generally yield low amounts of pulpwood and timber (Varmola & Salminen, 2004). Furthermore, young forests are often neglected in pre-commercial thinning in Sweden (cf. Anon., 2010a) and thus they often become dense and heterogeneous, in terms of tree size, by the time of first thinning. Nevertheless, stand density must be reduced to roughly 1 000 – 4 000 stems per hectare (cf. Hyytiainen et al., 2005) to permit favorable future economic development of the stand. The assortments that can be removed during thinning of such stands have little value for traditional purposes, hence small proportions of the biomass that could be extracted is currently utilized. This biomass represents a substantial potential source of fuel in Sweden (Nordfjell et al., 2008), and increases in demand and prices for bio-fuel in recent years (Anon., 2010b) have led to increasing use of such assortments. Hence, there is a need for new, cost-efficient, forest fuel harvesting techniques, methods and systems dealing with young dense stands.

Over the past decades, cut-to-length harvesting with single-grip harvesters have gained status as the dominant harvesting technology in Swedish forestry (Nordlund, 1996; Löfroth & Rådström, 2006). Single-grip harvester productivity depends on the size and number of removed trees per unit area (e.g. Kuitto et al., 1994; McNeel & Rutherford, 1994; Brunberg, 1997; Eliasson 1999; Nurminen et al., 2006). The conventional single-grip harvester handles one tree per boom work-cycle, which leads to low productivity (expressed as harvested volume per unit time) when harvesting small trees. Hence, harvesting operations in young stands often render poor economic return. Harvester productivity in such forests may be increased through handling several trees in one boom work-cycle (e.g. Johansson & Gullberg, 2002). Towards this end, Bergström et al. (2007) have compared the productivity potential of conventional and future (hypothetical) harvesting systems for forest fuel thinning (full trees) in young dense forests. They found that combining geometrical thinning systems (boom-corridor thinning) with customized techniques could increase productivity up to 2.4-fold. However, the scope of simulations presented by Bergström et al. (2007) was limited in terms of both the types of stands considered and repetitions, so more extensive analyses are required to assess the generality of the apparent potential productivity gains, and further quantify them. Improvements in forest technology for extracting biomass from young forests may lead to changes in forest management planning and practices (cf. Heikkilä et al., 2009). Oikari et al. (2010) list, and rank, a large number of approaches for increasing the cost-efficiency of harvesting in young stands, related (*inter alia*) to operator aspects, silviculture prior to thinning and changes to machinery, cutting techniques and working methods. Clearly, in order to assess the impact of such changes robustly, the costs (and benefits) of possible management practices with present and potential systems must be known or accurately estimated.

When developing new techniques, methods and systems, initial studies on the new concepts are typically comparative (e.g. Talbot et al., 2003). As a concept matures, correlation studies, i.e. analyses of the correlations between the productivity of a given technique, method or system with various environmental factors (e.g. Brunberg, 1997) are needed to provide a sound basis for decision-making and fair pricing of the work. Simulation models have been used in forest technology and work science for both comparative and correlation analyses for several decades (Newnham, 1966), and in many contexts, around the world (AedoOrtiz et al., 1997; Wang et al., 2005), as thoroughly reviewed by Wang and Greene (1999). Such models provide valuable, flexible tools for evaluating various possibilities, e.g. forest machine concepts that are not practically available today. Another advantage of simulations is the opportunity they provide to estimate time consumption (TC) for certain operations without having to perform them in reality. Hence, a particular activity can be performed several times with different settings, since the piece of work is not affected. Furthermore, a simulation approach eliminates variations in results due to uncontrollable factors, such as operator effects (Lindroos, 2008) and fluctuations in weather conditions. Rare work elements (non-cyclic) can also be excluded from the simulation model (Eliasson, 1999) as well as delays (Spinelli & Visser, 2008) of different kinds. This facilitates comparisons of the performance of alternative systems under ideal conditions. However, such simulations provide essential benchmarks that the performance of real-world systems may at best equal, and this needs to be accounted for when comparing the performance of potential systems to that of current systems in practice.

A simulation model may be either deterministic or stochastic (if random elements are included). Another way to categorize models is as static or dynamic (if the modeled system is affected by its own current and previous state). Finally, models can be categorized as continuous or discrete-event, depending on whether changes in the modeled system with time are calculated using functions that yield continuous values, or as a series of discrete events. In the forestry sector the term discrete-event simulation is often associated with queue simulation applied in logistics or supply chain management, where different machines interact with one another (e.g. Asikainen, 2010). However, strictly, the term discrete-event simulation only describes how time is handled in the model.

A simulation model of a single-grip harvester can provide fairly reliable productivity estimates for current machine concepts (Eliasson, 1999; Eliasson & Lageson, 1999; Wang et al., 2005). However, the quality of a simulation model is inevitably constrained by the quality of its algorithms and the input data, hence results from simulations should always be interpreted with caution. An alternative approach to assess the benefits of new machine concepts is to adjust functions used to describe systems known today. If a given change is expected to affect only some work elements (cf. Lindroos et al., 2008), the TC function for that work element may be altered on the basis of deductive reasoning (Gullberg, 1997). Previous simulation studies on forest fuel machinery have focused on comparing the performance of harvesters, and/or other machines, performing similar work in similar environments (e.g. Talbot & Suadicani, 2005; Bergström et al., 2007).

The objectives of this work were: i) to study the effects of different harvesting techniques, stand factors and thinning methods on time consumption for both present and future harvesting systems in young stand thinnings, and ii) to obtain productivity functions for such systems.

To our knowledge, this paper presents the first simulation model for assessing the performance of diverse permutations of single-tree-handling, multiple-tree-handling, selective and geometric felling harvesting systems and techniques in a wide range of environments. Thus, the model can be used for both comparative and correlative analyses.

Materials and methods

Datasets and software

The presented simulations have been performed using field data (Bredberg, 1972; Gustavsson, 1974) on individual tree characteristics (e.g. in Fig. 1) and tree positions (Cartesian coordinates). The datasets comprised 47 first thinning type stands with an original size of 25 × 40 m and 9 pre-commercial thinning type stands with an original size of 25 × 20 m.

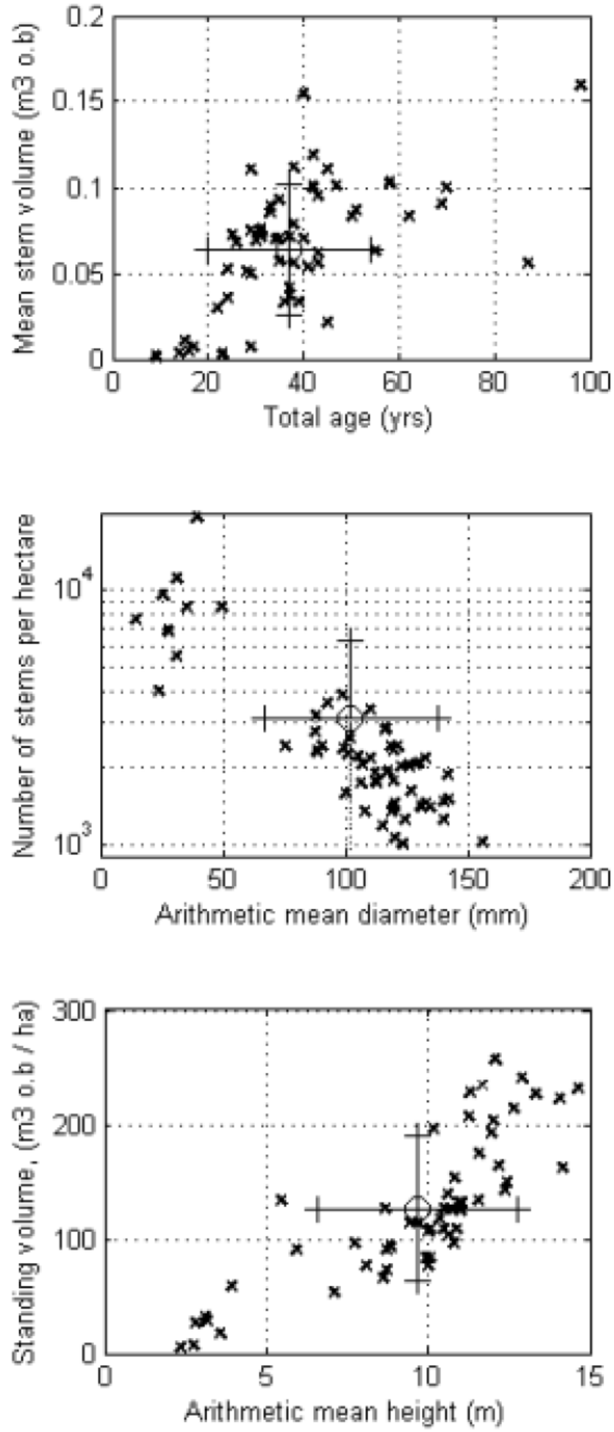


Figure 1. Characteristics of the 56 type stands used in the study, which were located at sites throughout most of Sweden, and had not been subjected to a first commercial thinning. The diameter of the trees was measured at breast height, 1.3 m above ground, and o.b. refers to over bark. Xs indicate individual observations, Os indicate mean values and the distances along the lines through the Os to the cross-lines indicate the standard deviations. Note: the lower end of the interval for number of stems per hectare is outside the graph.

Computer programming and simulations were performed using MATLAB R2009b software (The MathWorks, Inc., Natick, MA, USA), and Minitab 15 (Minitab, Inc., PA, USA) was used for statistical analysis of the results.

Approach and scenario definitions

The model used in the study presented here was based on the harvester simulation model developed by Eliasson (1999), with extended functionalities derived from other published simulation models (e.g. Santesson & Sjunnesson, 1972; Wang et al., 2005), felling operations in environments similar to those considered in this study (e.g. Bergström et al., 2007; Iwarsson Wide & Belbo, 2009) and harvester and forwarder working patterns (e.g. Gullberg, 1997; Ovaskainen et al., 2004; Ovaskainen et al., 2006; Ovaskainen, 2008). Functions describing new machine systems with boom-tip mounted, area-based felling devices and new working techniques were also implemented. In addition to the conventional single-tree-handling technique (e.g. Eliasson, 1999), multiple-tree-handling (e.g. Johansson & Gullberg, 2002) and geometrical harvesting in boom-corridors (Fig. 2) were simulated. The tree-based felling modes were all based on current technology, e.g. existing harvester heads. The area-based felling modes were imaginary in the sense that no commercial harvester heads can be applied in their current contexts, and were therefore based on assumptions about future technological developments (Bergström et al., 2007). Two area-based felling modes were modeled, designed to harvest a boom-corridor either in 2 m^2 segments or in a continuous felling movement. All harvest scenarios involved crosscutting the stems, and the forest fuel assortment obtained was assumed to be "rough-delimbed" tree sections, retaining 50% of their branches and needles. A model for transforming the type stands according to the desired machine width to be analyzed (Appendix I) and an algorithm for automatic tree selection (Appendix II) were created. In addition, we developed four algorithms affecting the harvester working pattern, depending on the harvest scenario (Fig. 3 – Fig. 6).

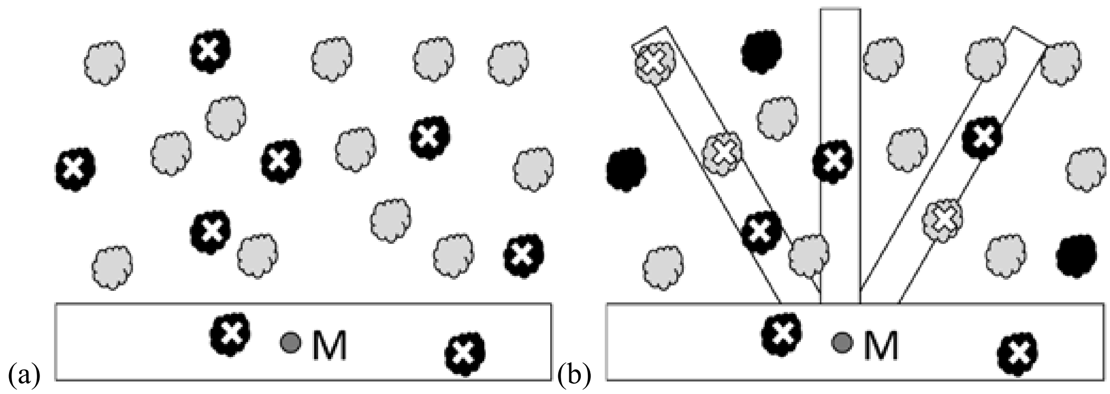


Figure 2. Examples of (a) selective harvest, and (b) geometrical harvest in boom-corridors (cf. Bergström et al., 2007), in identical stands. The machine-center position is indicated by M, Xs indicate trees actually cut, and black shading indicates trees selected for cutting under the selective system. The horizontal boxes in the lower parts of the figure indicate the strip road.

A strip road distance of 20 m was used in all the analyses, and the boom length, limiting the harvester working area, was 10 m. The strip road width was set to 4 m, and boom working area was defined according to Fig. 3b. Two thinning ratios of 0.9 and 1.1, defined as the arithmetic mean diameter at breast height (1.3 m above ground, DBH) of the extracted trees divided by the mean diameter of all trees before harvest, were applied in the models. Thinning intensity base levels were set to 30, 40 and 50% of the basal area. The base levels were multiplied by 1.1, 1.2 and 1.4 if the numbers of stems per ha before thinning were 2000-5000, >5 000-10 000, and > 10 000, respectively. The highest possible thinning intensity was thus 70%. This adjustment of thinning intensity was introduced in an attempt to obtain stands with a desired number of stems (roughly 1 000 – 4 000 per hectare) after each considered treatment. Nine combinations of techniques and systems, with various assortments were modeled, hereafter denoted using the abbreviations listed in Table I.

Table I. Simulated harvest scenarios (felling mode and applied harvest pattern between strip roads) and the acronyms used hereafter. RW and FF refer to roundwood and forest fuel, respectively. For the geometrical harvest patterns, corridor widths are given.

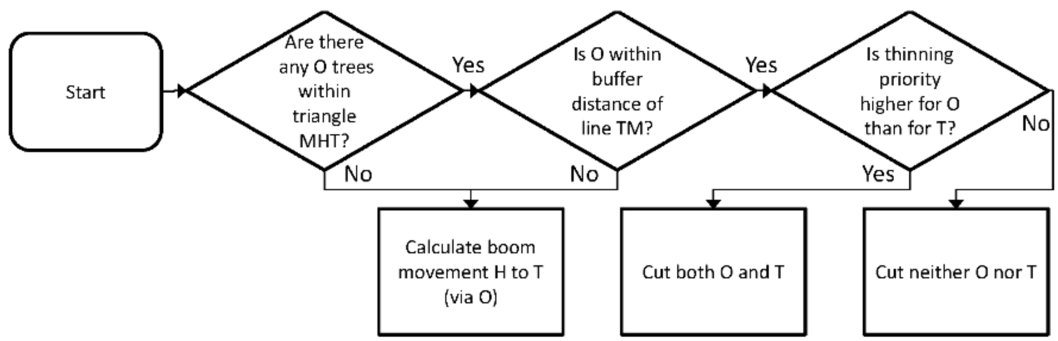
Harvest scenario				
Felling mode	Harvest pattern (between strip roads) and harvested assortment			
	Selective		Geometrical (corridor width)	
	RW	FF	FF (1 m)	FF (2 m)
Tree-based single-tree handling (TS)	$TSRW_{Sel}$			
Tree-based multi-tree handling (TM)	$TMRW_{Sel}$	$TMFF_{Sel}$	$TMFF_{Corr1}$	$TMFF_{Corr2}$
Area-based, felling 2m^2 at a time, multi-tree handling (2m^2)			$2m^2FF_{Corr1}$	$2m^2FF_{Corr2}$
Area-based, continuous felling, multi-tree handling (C)			CFF_{Corr1}	CFF_{Corr2}

The heterogeneity in tree spatial distribution per transformed type stand was described using the aggregation index (Clark & Evans, 1954), which is based on the average distance to the nearest neighboring tree and helps categorize tree spatial distributions as clustered, completely random (Poisson process) or with a tendency to regularity.

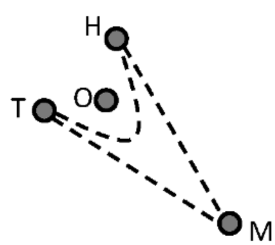
Model description

Our simulation model has stochastic elements in defining the environment, such as tree selection (Appendix II) and the machine start position calculation. However, the TC calculations are deterministic. The model is dynamic in the sense that TC for harvesting a particular tree varies, depending (for instance) on the position of the harvester relative to that tree and the number of trees accumulated in the harvester head in that particular work cycle. The model is discrete-event in the sense that it calculates TC for an entire work element (e.g. the boom movement between two trees) simultaneously, without tracking the boom's location in time and space on its path between trees. The simulated time in this study does not include delays and is best defined as productive work time (Björheden et al., 1995), denoted PWH when measured in hours, although some non-cyclic work elements that contribute to the productive work time must be subsequently added.

In the model, the machine moves between machine positions, identifies and harvests selected trees within boom reach at each position. Machine movements are generally simulated with a predefined distance (*YDE* , Table II), but this distance can be optionally shortened when harvesting selectively (cf. Fig. 4). The felling process at each machine position starts and ends with the harvester head at a default position, 2.5 m in front of the harvester. The order in which trees are harvested depends on tree position relative to the machine and harvest scenario. The entire model follows the basic flowchart in Fig. 7.



(a)



(b)

Figure 3. Algorithm for handling obstructing trees in selective harvest (a), as illustrated in (b). M indicates the machine center position, H the harvester head position, O an obstructing tree and T the next tree to be cut. O is avoided by incorporating buffer distances between O and H, at all positions of H on its path towards T. The buffer distances between H and the surface of tree O are 0.5 and 0.25 m along and perpendicular to the line OM, respectively. For the geometrical harvest scenarios, no perpendicular buffer distance is applied.

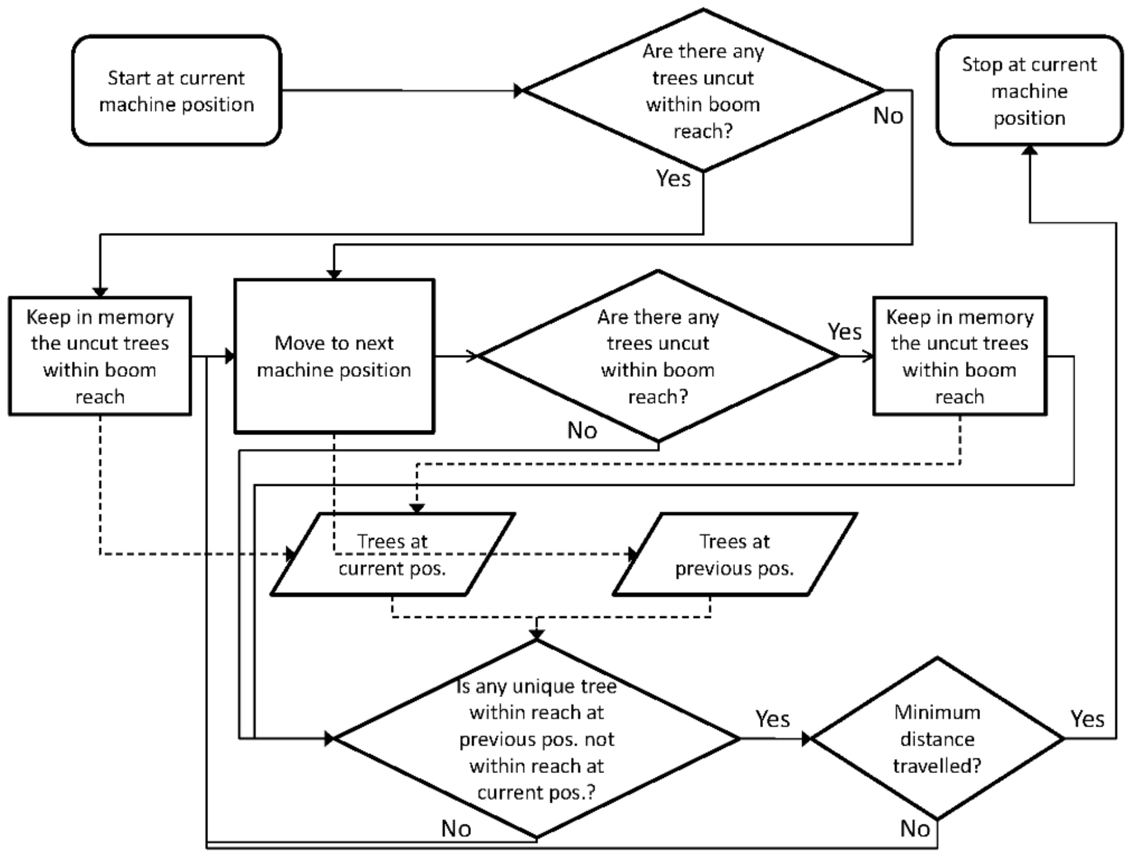


Figure 4. Algorithm for avoiding leaving trees selected for harvest uncut (cf. Santesson & Sjunnesson, 1972).

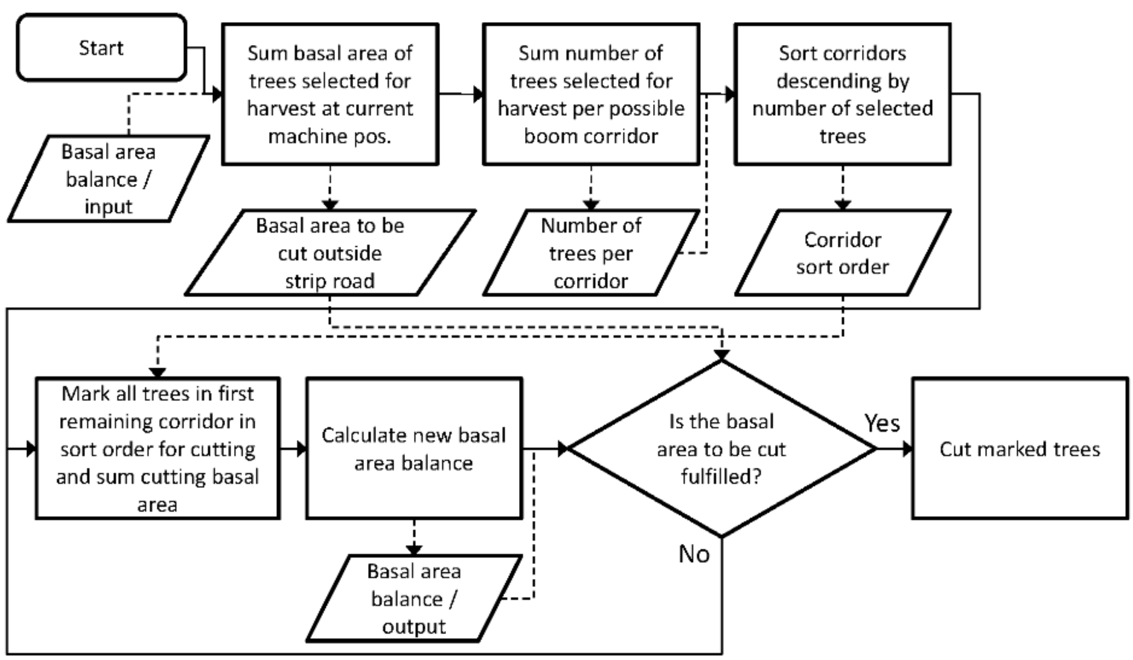
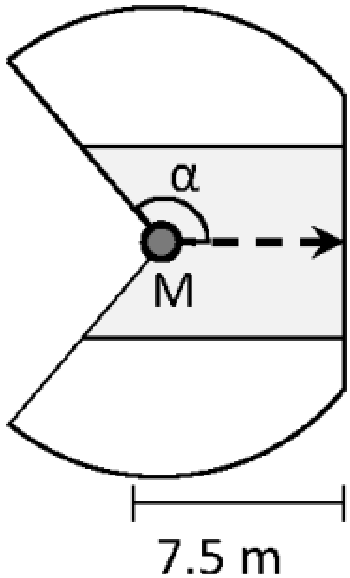
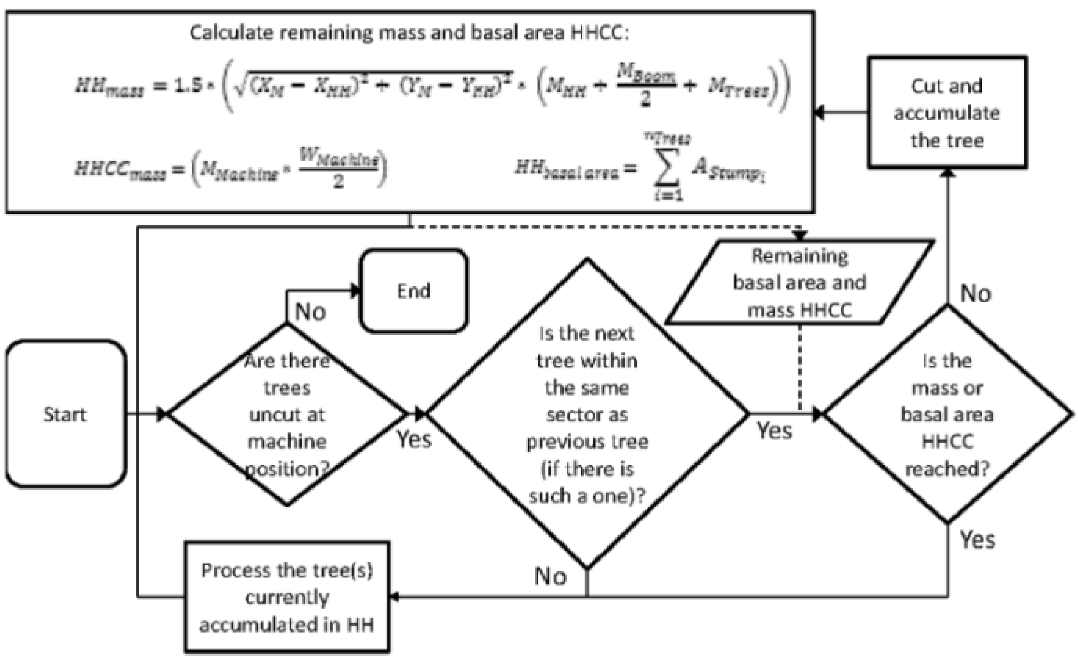


Figure 5. Algorithm for selectively laying out corridors for geometrical harvest. At every machine position, a maximum of six corridors (three per machine side at angles of 60˚, 90˚, and 120˚ relative to the machine's driving direction) are cut.



(a)



(b)

Figure 6. (a) Schematic diagram of harvester boom working sectors, showing the machine position (M) on a strip road (grey), the machine driving direction (arrow), forward limitation (imposed to restrict unnecessary boom movements) of 7.5 m of the boom reach in the driving direction, and maximum boom slewing angle (a) of 130˚. (b) Algorithm for multiple-tree harvesting. HHCC is the Harvester Head Carrying Capacity, and MTrees is the accumulated mass of all trees currently in the harvester head. The force exerted by the boom, harvester head, and accumulated trees is adjusted by a safety margin factor of 1.5 to abort the accumulation cycle well before the machine rolls over. For explanations of other terms, see Table II and the following text.

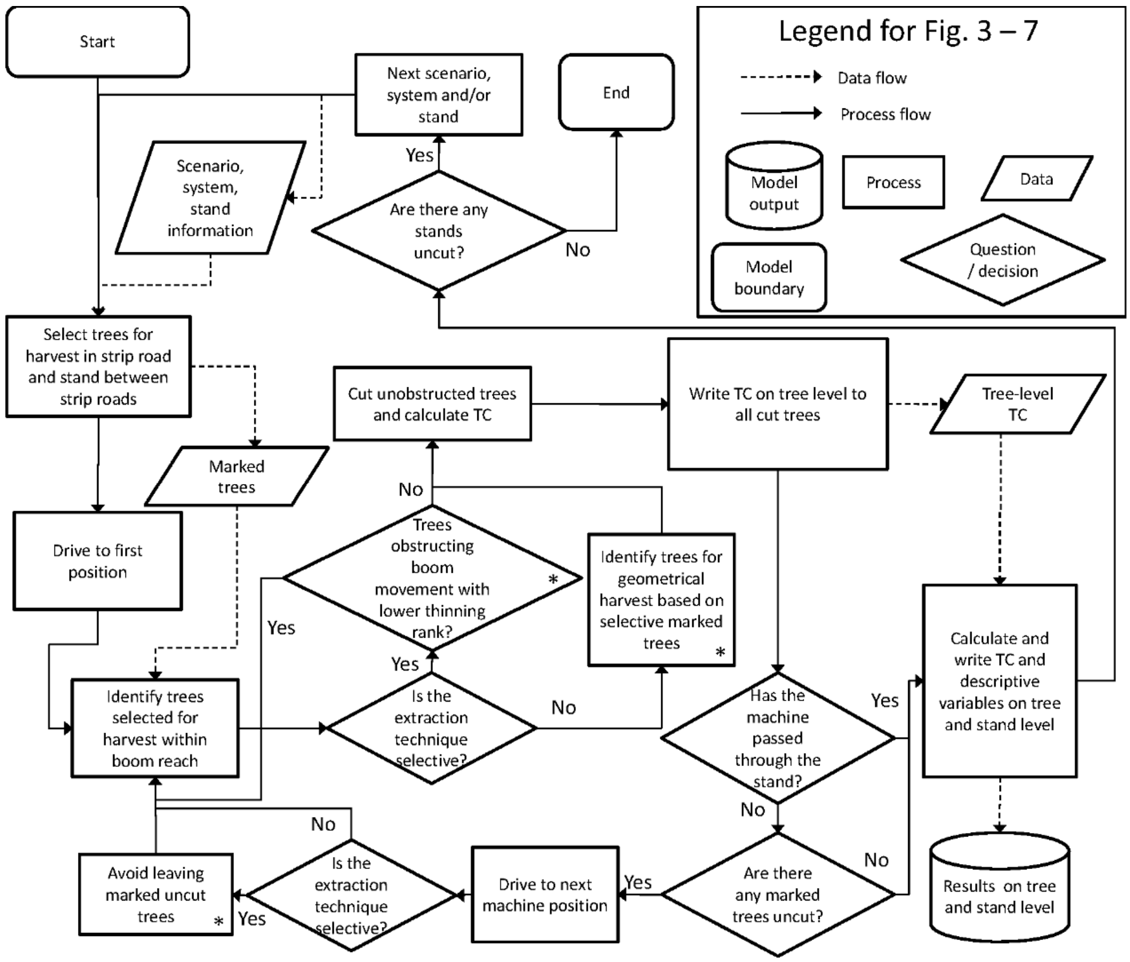


Figure 7. Simulation model flowchart, mainly after Eliasson (1999), but including additional functionalities (marked by *). The algorithms are described in detail in Figures 4 – 6. TC means time consumption.

The total TC per tree for harvester work is calculated from Eq. (1):

$$(1) \qquad T_{Tot} = T_{BoomOutIn} + T_{BoomInt} + T_{Fell} + T_{LimbCut} + T_{Move}$$

where T_{Tot} is total TC, $T_{BoomOutIn}$ is TC for boom movements towards the first tree to be cut in a work cycle, and towards the processing spot after cutting the last tree in a work cycle or the default harvester head position in front of the machine, $T_{BoomInt}$ is TC for boom movement between trees to be cut in the same work cycle, T_{Fell} is TC for felling trees, $T_{LimbCut}$ is TC for processing (i.e. delimbing and cross-cutting) trees and T_{Move} is TC for moving the machine between machine positions. All time elements in Eq. (1) – (3) and (6) – (8) are in seconds. TC values are calculated at tree, work cycle or stand level, as appropriate for the work element and harvest scenario. TC per calculation unit is then distributed equally among all trees handled in the calculation unit under consideration.

TC values for boom movements are calculated at work cycle level according to Eq. (2) for all boom movements if the felling mode is tree-based ($TSRW_{Sel}$, $TMRW_{Sel}$, $TMFF_{Sel}$, $TMFF_{Corr}$). For the area-based felling modes ($2m^2FF_{Corr}$, CFF_{Corr}) it is calculated according to Eq. (2) for boom movements out and in, and according to Eq. (3) for intermediate boom movements (between trees or within a work cycle). Processing spots at each machine position are selected at work cycle level as the best alternative of: i) a point located at the same side and angle of the machine as the harvester head, and one log length from the strip road side, or ii) a point located at the opposite side of the machine from the harvester head, at the strip road side, 2.5 m from the machine center position. The best alternative is considered as the spot giving the lowest TC for boom movement, according to Eq. (2). n_{Sub} is the number of submovements required for the boom to reach a particular tree, j is an index for a particular submovement, L is the radial distance in meters from the current harvester head position to its destination for each submovement (Eq. (4)) and α is the angular distance in degrees from the current harvester head position to its destination for each submovement (Eq. (5)).

(2) $$T_{BoomOutIn} = T_{BoomInt} = C_{Boom} + \sum_{j=1}^{n_{Sub}} \left(C_{BoomSub} + \max\left[\left(\frac{L}{v_{Boom}} \right)_j , \left(\frac{\alpha}{\omega_{Boom}} \right)_j \right] \right)$$

(3) $$T_{BoomInt} = C_{Boom} + \sum_{j=1}^{n_{Sub}} \left(C_{BoomSub} + \left(\frac{L}{v_{Boom}} \right)_j \right)$$

(4) $$L = \left| \sqrt{(X_M - X_{HH})^2 + (Y_M - Y_{HH})^2} - \sqrt{(X_M - X_{dest})^2 + (Y_M - Y_{dest})^2} \right|$$

(5) $$\alpha = \left| \alpha_{HH} - \alpha_{dest} \right|$$

In the above equations, X_M, Y_M, X_{HH}, Y_{HH}, X_{dest} and Y_{dest} are X- and Y-coordinates of the machine center, harvester head and submovement destination, respectively. α_{HH} and α_{dest} are the angles between the machine driving direction and the current boom angle and the submovement destination boom angle, respectively. Other constants used in the following text and equations are listed in Table II. TC for felling is calculated per work cycle, which may include the felling of several trees when -handling multiple trees. It is calculated according to Eq. (6), where n_{Trees} is the number of trees currently in the harvester head, A_{Stump_i} is stump area in cm^2 for tree i, and n_{Fell} is the number of initiated felling operations, which is one per tree (n_{Trees}) for the tree handling felling modes. For $2m^2FF_{Corr}$, n_{Fell} increases by one for every 2 m^2 containing at least one tree to be cut, and n_{Fell} for CFF_{Corr} is equal to the number of initialized work cycles required to harvest a corridor.

(6) $$T_{Fell} = n_{Fell} \times C_{Fell} + \sum_{i=1}^{n_{Trees}} \left(A_{Stump_i} \times v_{Fell} \right)$$

TC for processing (delimbing and cutting) is calculated per work cycle according to Eq. (7). n_{Logs} is the maximum number of logs to be cross-cut from any of the trees in the current working cycle calculated according to Eq. (11) and A_{i_l} is cross-cut area in cm^2 for any log l of any tree i. The feeding time for one Scots pine tree may be 1 s lower than for a Norway spruce or birch tree (Nuutinen et al., 2010). Therefore, we incorporated delimbing time correction factor, where $VolPine_i$ is the volume for tree i if the tree is a Scots pine.

(7) $$T_{LimbCut} = \frac{n_{Logs} \times L_{Log}}{v_{\mathrm{Proc}}} + C_{Feed\,\mathrm{Res}} \times n_{Logs} \times \frac{\sum_{i=1}^{n_{Trees}} Vol_i}{v_{Feed\,\mathrm{Res}}} - \frac{\sum_{i=1}^{n_{Trees}} VolPine_i}{\sum_{i=1}^{n_{Trees}} Vol_i} \times 1 + \sum_{l=1}^{n_{Logs}} \left(C_{CC} + \sum_{i=1}^{n_{Trees}} \left(A_{i_l} \times v_{Fell} \right) \right)$$

TC for machine movement is calculated at stand level according to Eq. (8), where n_{Move} is the total number of machine positions and X_M, X_{M-1}, Y_M and Y_{M-1} are the current and previous machine X- and Y-coordinates. For the geometrical harvest scenarios, $(Y - Y_{M-1})$ equals YDE .

(8) $$T_{Move} = \sum_{m=1}^{n_{Move}-1} \left(C_{Move} + \sqrt{(X_M - X_{M-1})^2 + (Y_M - Y_{M-1})^2} \times v_{Move} \right)$$

For calculating stem commercial lengths when harvesting roundwood (H_{CMD}, m) and cross-cutting areas, stem taper is approximated according to one of the following approaches. If the DBH is > 7.5 cm, the section of each stem above the 7.5 cm diameter height ($H_{7.5}$, m) up to total tree height (H_{tot}, m) is approximated by a bulging cone, whose form depends on tree diameter, height and volume (Vol , m^3), and the height (in meters) to the commercial minimum diameter on bark (CMD, cm) is calculated according to Eq. (9):

$$\text{(9)}\quad H_{CMD} = \min\left[\left(H_{7.5} + \left(H_{tot} - H_{7.5}\right) \times \frac{7.5 - CMD}{7.5} \times \frac{Vol \times 3}{H_{tot} \times \left(DBH/200\right)^2 \times \pi}\right), \left(H_{tot} - 1\right)\right]$$

If DBH is ≤ 7.5 cm and ≥ CMD, the height (in meters) is calculated according to Eq. (10):

$$\text{(10)}\qquad H_{CMD} = \min\left[\left(1.3 + \frac{DBH - CMD}{DBH \times \left(H_{tot} - 1.3\right)^{-1}} \times \frac{Vol \times 3}{H_{tot} \times \left(DBH/200\right)^2 \times \pi}\right), \left(H_{tot} - 1\right)\right]$$

If DBH < CMD the height to the minimum commercial diameter is considered zero, since commercial log lengths are typically longer than 1.3 m. The number of logs to be cut in each working cycle is calculated as the highest number of logs from any of the j trees currently in the harvester head, according to Eq. (11):

$$\text{(11)}\qquad n_{Logs} = \left\lfloor \frac{\max\left(H_{CMD}\right)_j}{L_{\log}} \right\rfloor \qquad \text{(number of logs)}$$

Values for the model parameters are given in Table II. We assigned machine characteristics on the basis of Eliasson's (1999) values and manufacturer information (Anon., 2008a; Anon., 2008b; Anon., 2010c). In many cases TC coefficients are the same as Eliasson's, but for certain work elements we altered the coefficients. For example, we increased C_{Fell} in accordance with several recent time studies on harvester performance, both in thinning in general (Nurminen et al., 2006) and forest fuel thinning in young stands in particular (e.g.

Bergström, 2009; Iwarsson Wide & Belbo, 2009; di Fulvio, 2010). Distances between machine positions were chosen on the basis of Eliasson's (1999) results, as well as knowledge of pile size effects on forwarder performance (e.g. Gullberg, 1997). In the selective harvest scenarios, however, the actual distance between machine positions varied between YDE_{Min} and YDE.

Table II. Scenario settings, machine characteristics and model coefficients used in the simulations. When a particular variable takes different values for different harvest scenarios, scenarios (explained in Table I) are indicated in superscript letters.

Parameter	Symbol	Values	Unit
Max. basal area in harvester head	$HHCC_{basal\_area}$	$845^{\text{TSRWSel, TMRWSel, TMFF}}$, $-^{\text{2m2FFCorr, CFFCorr}}$	cm^2
Harvester head mass	M_{HH}	700	kg
Boom mass except boom pillar	M_{Boom}	1 000	kg
Base machine mass including boom pillar	$M_{Machine}$	14 800	kg
Base machine balance width	$W_{Machine}$	2.19	m
Maximum distance between machine positions	YDE	5	m
Minimum distance between machine positions	YDE_{Min}	2^{Sel}, 5^{Corr}	m
Constant for machine moving time	C_{Move}	5	s
Machine moving speed	V_{Move}	1	m/s
Constant for boom movement	C_{Boom}	1.5	s
Constant for boom sub-movement	$C_{BoomSub}$	0.1	s
Boom speed, radial	v_{Boom}	2.5	m/s
Boom speed, angular	ω_{Boom}	20	°/s
Log length	$L_{\log}$	$4.2^{\text{TSRWSel, TMRWSel}}$, $5.5^{\text{TMFF, 2m2FFCorr, CFFCorr}}$	m
Min. top diameter on bark for utilized stem parts	CMD	$5^{\text{TSRWSel, TMRWSel}}$, $0^{\text{TMFF, 2m2FFCorr, CFFCorr}}$	cm
Feeding speed	$v_{\Pr oc}$	1.5	m/s

Constant for processing	$C_{Feed\,\mathrm{Res}}$	0.8	s
Volume of reference tree for processing	$V_{Feed\,\mathrm{Res}}$	0.18	m^3
Constant for delimbing	C_{Limb}	2	s
Constant for positioning at felling	C_{Fell}	3	s
Felling speed	v_{Fell}	800	cm^2/s
Constant for cross-cutting	C_{CC}	1	s

The experimental design in this study is a randomized block factorial (RBF) experiment. The 56 stands are the main blocking units. Within each block harvest scenario, the desired thinning ratio and desired thinning intensity base level are the factors. For each stand and combination of blocks and factors two repeated simulations were run, using different (randomized) starting points and slightly different tree selections (Appendix II). In total, 6 048 simulations were run, with an execution time of around 28 hrs on a PC with a 2.8 GHz processor and 3 GB of RAM.

Analysis and parameters

Differences in TC related to the factors involved in the RBF-experiment were investigated using analysis of variance (ANOVA) with the following model:

$$y_{shiqo} = \mu + a_s + b_h + c_i + d_q + (ab)_{sh} + (ac)_{si} + (ad)_{sq} + (bc)_{hi} + (bd)_{hq} + (cd)_{iq} + \\ + (abc)_{shi} + (abd)_{shq} + (acd)_{siq} + (bcd)_{hiq} + (abcd)_{shiq} + e_{shiqo}$$

where y_{shiqo} is an individual observation of TC per tree, μ is the grand mean, a_s is the random block effect of stand s, b_h is the harvest scenario effect for harvest scenario h, c_i is the thinning intensity effect for thinning intensity base level i and d_q is the thinning ratio effect for thinning ratio class q. Interactions between factors are included and denoted, for instance, $(ab)_{sh}$ which is the interaction effect of stand and harvest scenario, and finally e_{shiqo}

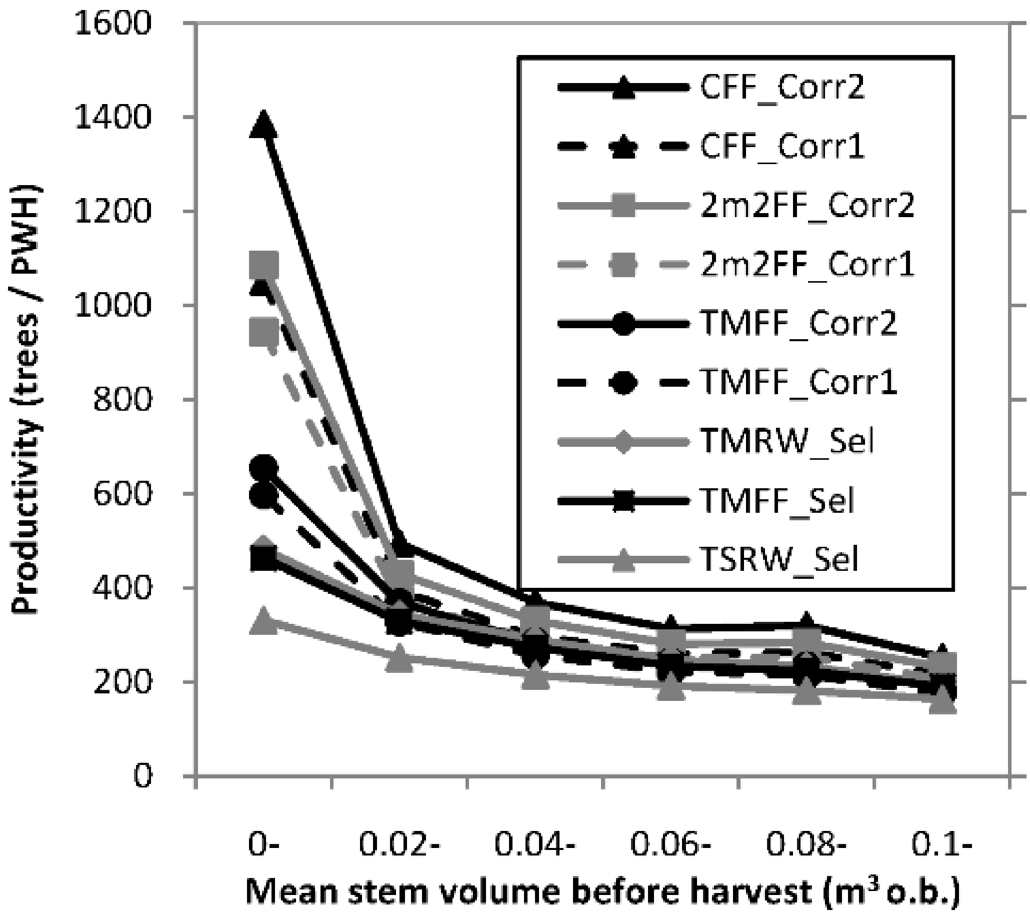
is the error term for the individual observation o. Harvest scenarios were compared pairwise, by applying Tukey's test based on a limited version of the model above, including only the main effects of stand (a_s) and harvest scenario (b_h). The effects of stand characteristics and experimental factors were investigated using correlation and regression analysis in an iterative process. The aims of this analysis were both to clarify relationships and to obtain general productivity estimates for the different harvesting systems under different conditions.

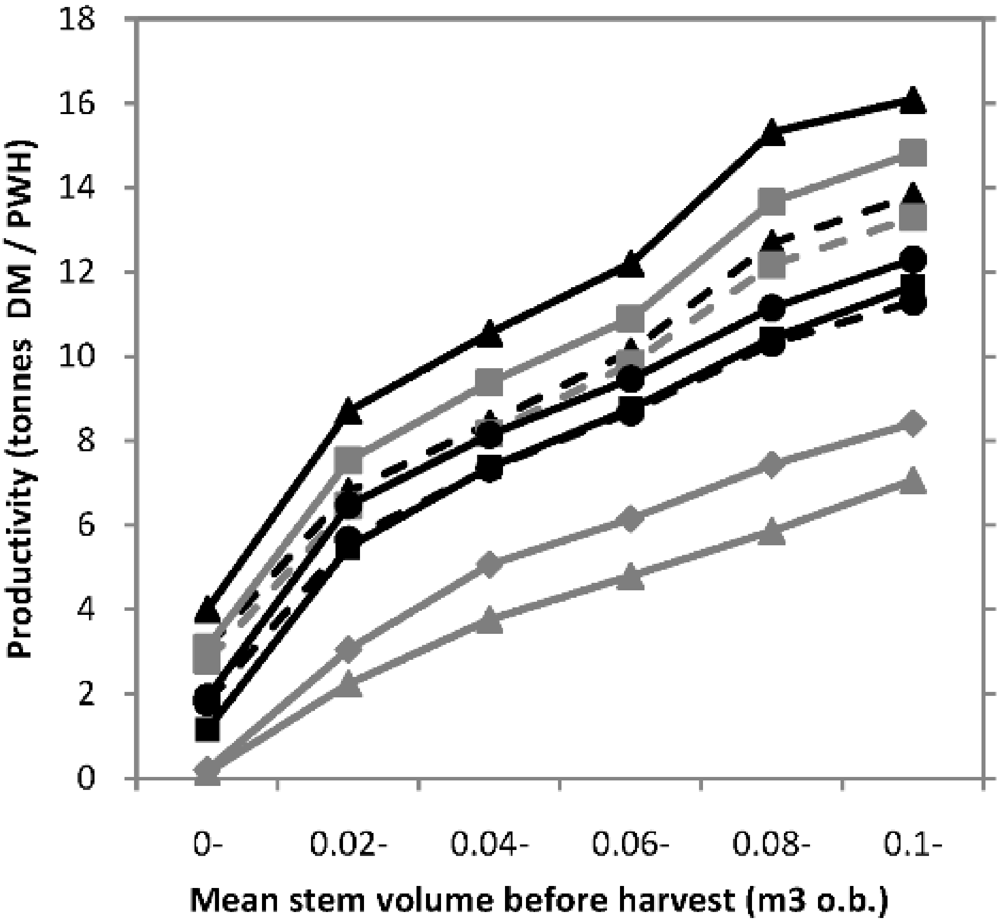
Results

According to the ANOVA, all main effects and all first-order interactions but $(cd)_{iq}$ had significant ($p < 0.001$) effects on TC. Several second- and third- order interactions also affected TC ($p < 0.001$). However, the stand and harvest scenario main effects explained (by far) the largest amounts of the variance. For the selective harvest scenarios, TC per tree when thinning from above (mean thinning ratio 1.02) was on average 1.1 s, or 7.4%, significantly higher than when thinning from below (mean thinning ratio 0.94). For the geometric harvest scenarios, no significant differences related to target thinning ratio were found. TC per tree significantly decreased with increasing thinning intensity in all harvest scenarios. Differences between harvest scenarios are presented as total means in Table III and differences between different mean stem volume classes in Fig. 8.

Table III. Mean time consumption (TC) per tree and harvest scenario for all stands and simulations. Significant differences ($p < 0.01$) between harvest scenarios, according to the pairwise comparisons are indicated by different superscript letters. For abbreviations, see Table I.

Harvest scenario	$TSRW_{Sel}$	$TMRW_{Sel}$	$TMFF_{Sel}$	$TMFF_{Corr1}$	$TMFF_{Corr2}$	$2m^2FF_{Corr1}$	$2m^2FF_{Corr2}$	CFF_{Corr1}	CFF_{Corr2}
TC (s)	17.49[a]	13.53[b]	14.15[c]	14.62[c]	13.35[b]	12.59[d]	11.18[e]	12.09[d]	10.04[f]


Productivity (trees / PWH)
1600
1400
1200
1000
800
600
400
200
0
CFF_Corr2
CFF_Corr1
2m2FF_Corr2
2m2FF_Corr1
TMFF_Corr2
TMFF_Corr1
TMRW_Sel
TMFF_Sel
TSRW_Sel
0-
0.02-
0.04-
0.06-
0.08-
0.1-
Mean stem volume before harvest (m3 o.b.)
(a)



(b)

Figure 8. Mean productivity values obtained from the simulations, expressed as (a) trees harvested per productive work hour (PWH) and (b) tonnes dry matter (DM) of the given assortment harvested per PWH, for the classes of stand mean stem volume in m3 over bark (o.b.) indicated by the lower limits on the x-axes. Different lines indicate values for different harvest scenarios, as explained in the legend (cf. Table I). The forest fuel assortment in the simulations illustrated in (b) is defined as entire stems and 50% of other biomass above ground. The simulations included all 56 type stands, with 9, 6, 9 14, 9, and 9 stands in the classes from left to right, respectively.

Some characteristics of the simulated operations and extractions are presented in Fig. 9 and Table IV. Stand-level mean distances between machine positions for the selective harvest scenarios were on average 3.88 m, with minimum and maximum around 2 and 5 m respectively. TC per tree for boom movements and moving generally decreased with increased stand density, whereas the proportion of boom time spent on relocating the harvester head between trees in a work cycle increased (Table V). TC for felling depended on tree characteristics and, for the geometrical felling devices also on stand density. TC for processing depended on tree characteristics and also on stand density when handling multiple trees. Spatial variation (as defined by Clark and Evans (1954)) was highly correlated with several stand characteristics, such as the ratio between basal area-weighted mean diameter and basal area mean stem diameter, and often showed significance when tested for inclusion in the final regression functions. An increase in spatial variation (clustering of the trees) seemed to lead to lower total time consumption per tree in our simulations. The diameter ratio also had a significant effect on TC for boom movement for almost all harvest scenarios (Table V). Total boom movement time decreased and the proportion of boom time movement between trees increased as the diameter ratio increased, corresponding to an increase in spatial variation.

Table IV. Characteristics of the simulated operations and extractions. Work cycle level data calculated for all 6 048 simulations. DM means dry matter. Examples of extraction results related to the algorithms intended to mimic selectivity (Fig. 4 – Fig. 6) are presented as aggregates for each harvest pattern. Relative selectivity is calculated as follows. In the geometric harvest pattern illustrated in Fig. 2b), eight of 20 trees, two of which are located in the strip road, are selected for cutting. Thus, six of 18 trees outside the strip road are to be cut. If six trees were re-selected for cutting randomly, on average two of the originally selected trees would be selected again. In Fig. 2b), three of the originally selected trees are cut, and the *relative selectivity,* on top of randomness, is thus (3 – 2) / (6 – 2) = 25%.

Harvest scenarios	*Accumulated per work cycle*						*Extraction characteristics*				
	Number of trees			Biomass (kg DM of given assortment)			Relative selectivity (%)	Proportion of all trees (%)		Mean distance from strip road center to trees	
	Mean	Max	SD	Mean	Max	SD		Cut, not selected	Uncut, selected	Selected for cutting	Finally cut
$TSRW_{Sel}$	1.00	1.0	0	22.5	72.0	14.8					
$TMRW_{Sel}$	2.93	11.6	2.00	43.9	103	23.1	*58.7*	*3.1*	*6.7*	*5.71*	*5.21*
$TMFF_{Sel}$	2.91	11.4	1.96	68.1	125	29.0					
$TMFF_{Corr1}$	2.76	14.8	2.20	66.4	133	28.7					
$2m^2FF_{Corr1}$	2.95	16.1	2.21	74.9	189	36.9	*4.9*	*14.6*	*15.4*	*5.71*	*5.47*
CFF_{Corr1}	2.98	16.3	2.27	75.5	247	38.6					
$TMFF_{Corr2}$	3.49	17.4	3.06	77.5	153	30.6					
$2m^2FF_{Corr2}$	4.12	27.1	3.47	98.0	242	46.3	*13.6*	*14.0*	*14.0*	*5.70*	*5.59*
CFF_{Corr2}	4.17	24.7	3.51	101	256	50.0					

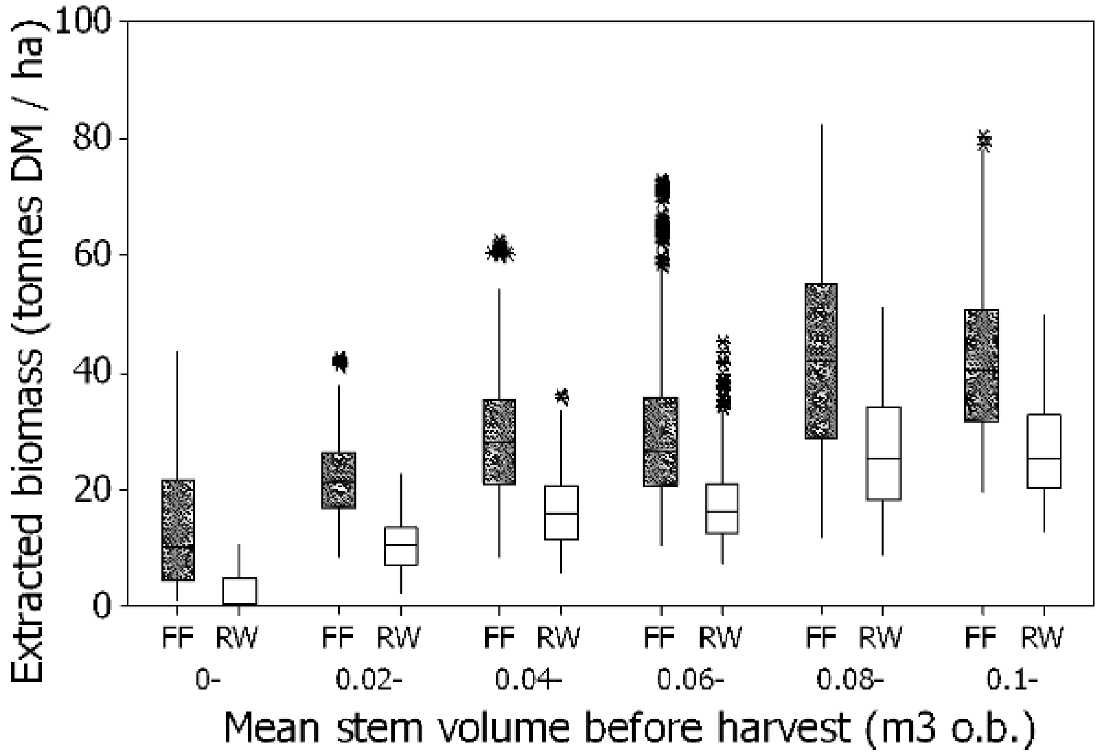


Figure 9. Boxplot (showing quartiles, minimum and maximum values, and outliers) of biomass [tonnes dry matter (DM)] extracted as forest fuel (FF) and roundwood (RW) per unit area on the y-axis, for classes of stand mean stem volume in m3 on bark (o.b.) indicated by the lower limits on the x-axis. The simulations included all 56 type stands, with 9, 6, 9, 14, 9, and 9 stands in the classes from left to right, respectively.

Table V. Regression coefficients for element-wise time consumption (TC) per tree in seconds for the considered harvest scenarios (cf. Table I). All coefficients are significant ($p < 0.05$). ProcTree is defined in Eq. (7), MoveTree in Eq.(8), FellTree in Eq. (6), BoomTree is calculated as Eq. (2) + Eq. (3) and Int% is calculated as the sum of the time consumption for all intermediate boom movements divided by the sum of the time consumption for all boom movements (for the area-based felling modes, Int% is thus Eq. (3) / (Eq. (2) + Eq. (3)) × 100). All parameters describing stand characteristics are stand mean values before harvest. The regression functions are only applicable to stands with characteristics similar to those illustrated in Fig. 1. As an example, the function for processing in $TSRW_{Sel}$ has the form ProcTree = 1.0008 × $e^{(-2.40 - 0.0163 \times ThIntStem + \ldots)}$.

Harvest scenario	TC per tree and work element, s	R^2	q	Constant	ThIntStem	ThIntBA	ExtNha	$ExtNha^{0,5}$	ExtVolHa	ThRatio	CorrW2	N	N^{-2}	N^{-1}	MStemVol	$MStemVol^2$	$MStemVol^{0,5}$	H^a	Dbh^a	H^a/Dbh^a	Dbh^b	Dbh^a/Dbh^b	PinePerc
					Thinning intensity (stems)	*Thinning intensity (basal area)*	*Extracted stems (N) per hectare*		*Extracted volume roundwood per hectare*	*Thinning ratio*	*Corridor width 2 m (else 1 m)*	*Number of stems before harvest*			*Mean stem volume before harvest*			*Mean height before harvest*	*Mean diameter before harvest*		*Mean diameter before harvest*		*Pine percentage of volume before harvest*
					%	%	ha^{-1}		m3 o.b.× ha^{-1}		0/1	ha^{-1}			m^3 o.b.			m	cm		cm		%
$TSRW_{Sel}$	ProcTree	0,990	1,0008	-2,40E+0	-1,63E-2	5,04E-3	-1,89E-4	4,18E-2		8,49E-1		-4,77E-5	-5,76E+5	1,48E+3		-2,29E+1	4,78E+0	8,55E-2	-1,47E-1	-2,05E-1	1,56E-1	6,32E-1	-1,73E-3
	MoveTree	0,986	1,0030	1,11E+0	-2,10E-2		6,57E-5	-1,25E-2		-1,15E-1		-5,88E-5	-3,06E+5	1,38E+3								1,70E-1	
	FellTree	0,971	1,0000	9,41E-1	-1,36E-3	7,24E-4	-1,20E-5	2,59E-3		7,58E-2		-1,31E-6	-9,43E+4	1,55E+2	2,07E+0	-3,09E+0	-1,19E+0	3,30E-3	3,57E-3		1,55E-2	-1,30E-2	
	BoomTree	0,813	1,0011	1,38E+0	-7,82E-3	-4,84E-3	-5,48E-5	1,38E-2		3,72E-1		-1,58E-5	-4,15E+5	8,39E+2								-7,53E-2	
$TMRW_{Sel}$	ProcTree	0,991	1,0020	-1,54E+0	-1,78E-2	1,40E-2	8,22E-5	-1,79E-2	4,78E-3			-2,95E-5		5,68E+2			-8,32E+0	1,99E-1	-9,02E-2		3,07E-1	5,13E-1	-1,43E-3
	MoveTree	0,986	1,0032	1,38E+0	-1,58E-2	-2,80E-3	1,05E-4	-2,39E-2	-3,47E-4			-4,21E-5		8,26E+2								1,49E-1	
	FellTree	0,972	1,0000	8,94E-1	-1,45E-3	7,68E-4	-1,31E-5	2,82E-3		7,68E-2		-1,67E-6	-9,95E+4	1,61E+2	1,72E+0	-2,51E+0	-9,39E-1		4,16E-3	2,59E-2	1,47E-2		
	BoomTree	0,868	1,0018	1,22E+0	-1,26E-2			1,52E-2	1,71E-3	-1,07E-1		-5,28E-5	-2,96E+5	1,04E+3									
	Int%	0,818	1,0106	8,82E+0		3,12E-2	2,53E-3	-6,90E-2	-9,19E-3	-2,60E+0		8,54E-5	2,37E+6	-5,12E+3									
$TMFF_{Sel}$	ProcTree	0,985	1,0025	-9,98E-1	-2,78E-2	1,54E-2		2,31E-2	2,13E-3			-1,05E-4	-5,91E+5	1,59E+3	3,21E+0	-2,08E+1		1,09E-1	-2,79E-2		7,82E-2		-9,09E-4
	MoveTree	0,985	1,0031	8,62E-1	-1,10E-2	-7,82E-3	9,40E-5	-2,20E-2	-5,90E-4	5,51E-1		-4,17E-5		8,68E+2								8,55E-2	
	FellTree	0,971	1,0000	9,00E-1	-1,50E-3	6,27E-4	-1,44E-5	3,21E-3	6,67E-5	7,71E-2		-2,26E-6	-1,13E+5	1,89E+2	1,84E+0	-2,54E+0	-1,06E+0		5,45E-3	2,75E-2	1,42E-2	-1,05E-2	
	BoomTree	0,892	1,0018	7,74E-1	-1,73E-2		-6,43E-5	3,02E-2	1,93E-3			-6,54E-5	-6,56E+5	1,76E+3								-5,84E-2	
	Int%	0,820	1,0117	6,34E+0	3,18E-2		2,24E-4	-6,96E-2	-9,73E-3			1,09E-4	2,28E+6	-4,98E+3								-1,59E-1	
$TMFF_{Corr}$	ProcTree	0,989	1,0011	-4,84E+0			4,64E-5	-1,20E-2	4,10E-3	9,02E-1	-1,33E-1	-2,78E-5	-1,13E+6	2,16E+3	-2,85E+1	6,39E+1		1,42E-1	-9,29E-2	7,32E-1	3,74E-1	1,01E+0	-1,47E-3
	MoveTree	0,997	1,0018	-2,90E-2	-7,18E-3	-1,02E-2	1,48E-4	-2,45E-2	-2,51E-4	9,60E-1	-6,70E-3	-6,22E-5	-6,39E+5	1,90E+3								6,51E-2	
	FellTree	0,970	1,0000	8,64E-1	-7,15E-4		-8,05E-6	2,51E-3		1,21E-1		-3,69E-6	-1,10E+5	1,68E+2	1,50E+0	-1,90E+0	-7,15E-1	-3,12E-3	8,09E-3	4,91E-2	8,72E-3	-1,46E-2	
	BoomTree	0,973	1,0023	5,90E-1		-3,71E-3	2,08E-5		2,24E-3	4,42E-1	-1,74E-1	-4,85E-5	-1,02E+6	2,15E+3								-8,41E-2	
	Int%	0,847	1,0104	3,43E+0		-8,31E-3		1,30E-2	-3,83E-3		8,01E-2		1,44E+6	-1,79E+3									
$2m^2FF_{Corr}$	ProcTree	0,988	1,0009	-4,94E+0				-4,91E-3	4,27E-3	8,03E-1	-2,12E-1	-2,74E-5	-1,35E+6	2,82E+3	-4,16E+1	8,95E+1	7,68E+0	1,28E-1	-1,27E-1	5,24E-1	2,99E-1	1,13E+0	-1,23E-3
	MoveTree	0,997	1,0017	2,83E-1	-1,12E-2	-6,43E-3	1,53E-4	-2,43E-2	-2,62E-4	6,87E-1	-4,99E-3	-6,74E-5	-5,78E+5	-1,82E+3								6,17E-2	
	FellTree	0,942	1,0027	2,33E-1	-8,44E-3	4,55E-3	-6,18E-5	1,79E-2	1,22E-3		1,14E-1	-6,97E-5	-8,49E+5	1,44E+3	-1,47E+1	2,67E+1	8,71E+0	-3,31E-2		-1,96E-1	-6,10E-2	-2,05E-1	
	BoomTree	0,967	1,0026	1,40E+0		4,13E-3	5,97E-5	-1,39E-2	6,31E-4		-2,25E-1	-3,13E-5	-6,62E+5	1,41E+3								-1,54E-1	
	Int%	0,840	1,0098	3,24E+0	-1,44E-2	-6,95E-3		2,67E-2			2,30E-1	-4,69E-5	8,31E+5	-1,16E+3									
CFF_{Corr}	ProcTree	0,987	1,0013	-5,78E+0	9,29E-3	-9,58E-3	-2,86E-5		4,03E-3	1,48E+0	-2,20E-1	-2,57E-5	-1,33E+6	2,90E+3	-4,54E+1	9,64E+1	9,34E+0	1,29E-1	-1,41E-1	4,08E-1	3,04E-1	1,15E+0	-1,13E-3
	MoveTree	0,996	1,0019	3,52E-1	-1,11E-2	-5,94E-3	1,54E-4	-2,59E-2	-2,89E-4	6,33E-1	-6,07E-3	-6,26E-5	-5,76E+5	1,79E+3								6,82E-2	
	FellTree	0,969	1,0027	-2,97E-1	6,32E-3			-6,90E-3	1,68E-3	4,00E-1	-2,52E-1	-3,67E-5	-1,14E+6	2,05E+3	-8,24E+0	1,93E+1	3,98E+0			-3,23E-1	-3,48E-2	-3,15E-1	
	BoomTree	0,957	1,0026	1,15E+0	2,14E-3				5,02E-4	1,46E-1	-2,32E-1	-4,47E-5	-6,93E+5	1,61E+3								-3,04E-1	
	Int%	0,809	1,0116	3,03E+0	-1,49E-2	-4,98E-3		2,18E-2			2,49E-1	-3,26E-5	7,00E+5	-9,74E+2								1,27E-1	

Parameter, *explanation*, unit

Discussion

In our simulations productivity increased with increasing boom-corridor width for all felling modes (Table III), due partly to reductions in boom TC (Table V) and the associated increase in number of trees handled per processing cycle (Table IV). Too wide boom-corridors may lead to reductions in growth of total or commercial volume in a short- or medium term perspective (Pettersson, 1986). This growth reduction may however (for reasonable removals and remaining stand densities) be compensated for in a long-term perspective (Karlsson et al., 2011), and the cited authors attribute some of the growth reductions to reduced selectivity rather than the geometrical harvest pattern *per se*. Even in selective thinning, some of the extraction in first thinning is always unselective, as trees in the paths of strip roads must be removed (eg. 24 – 34% of removal in Lageson (1997)). Similarly, in our simulations the geometric harvest scenarios were still to some extent selective outside the strip roads (Table IV), but the maximum number of possible boom-corridors constrained relative selectivity (Fig. 6), leaving little room for selectivity at high extraction rates. This constraint on selectivity was more pronounced with the narrower boom-corridors, due to the lower maximum boom-corridor area. Deciding the optimal corridor width is not straightforward, since it is affected not only by machine and stand characteristics, but also by the weighting of economic variables with different time horizons. Furthermore, nutrient removal caused by full tree harvesting may inhibit growth of young stands (cf. Mård, 1998; Jacobson et al., 2000). To assess these effects efficiently and thoroughly, stand level growth and yield analysis using an optimizing approach may be required.

The thinning intensity and thinning ratio effects on TC in our simulations are consistent with earlier findings for the area (e.g. Brunberg, 1997; Eliasson, 1999; Eliasson & Lageson, 1999). The observed effects on TC of spatial variation (as defined by Clark and

Evans (1954)) in the stands were difficult to quantify due to correlations with other independent variables. Since spatial variation is not measured in an ordinary stand inventory it was not included in the final regression functions (Table V). For equivalent tree sizes the differences we obtained in productivity (Table III, Fig. 8) were of the same order of magnitude as those found by Bergström et al. (2007). The difference between e.g. $TSRW_{Sel}$ and $TMRW_{Sel}$ seemed to decrease with increasing tree size (Fig. 8), in line with previous findings (e.g. Johansson & Gullberg, 2002). The differences in relationships between the scenarios illustrated in Fig. 8 a) and Fig. 8 b) are noteworthy, since the roundwood scenarios had much lower productivity than the forest fuel scenarios in terms of the amount of biomass harvested per unit time than in terms of harvested numbers of stems per unit time (see also Fig. 9). Other assumptions regarding the degree of utilization of needles and branches would have led to other results for the forest fuel scenarios illustrated in Fig. 8b. If no needles or all needles and branches are utilized, the FF curves should be altered by factors of 0.85 and 1.15, respectively. This factor is also tree-size-dependent, with greater deviations from 1 for very small trees. Changes in CMD (Table II) would also lead to other results, i.e. a greater difference in CMD between RW and FF would change the relative differences in Fig. 8 and Fig. 9.

TC values for $TMFF_{Corr}$ were intermediate between those of $TMFF_{Sel}$ and $2m^2FF_{Corr}$, indicating that the geometrical harvest pattern *per se* has a positive effect on productivity. For the selective harvest scenarios, fewer trees were cut than selected, even though some of the obstructing trees (not selected) were cut to access selected trees (Table IV). For all harvest scenarios, the cut trees were located somewhat closer to the strip road than the selected trees (Table IV). These effects are results of the algorithms for (*inter alia*) obstacle avoidance illustrated in Fig. 3, Fig. 4 and Fig. 5. Thus, pre- and post-treatment thinning intensities and ratios were rarely the same, in contrast to the simulations reported by Eliasson (1999), in which only one tree was left behind in total. However, it should be noted that Eliasson considered some of the least dense stands included in our simulations.

The simulation model applied in this study does not consider effects of the surrounding trees when harvesting a tree, although positioning times and crown resistance are both likely to be higher in denser stands (Santesson & Sjunnesson, 1972), and even more so when the harvester head already contains previously accumulated trees. If this had been considered in the model, $TMRW_{Sel}$ and $TMFF_{Sel,Corr}$ would have had a somewhat poorer performance, relative to both $TSRW_{Sel}$, $2m2FF_{Corr}$ and CFF_{Corr} (Table III). In real-life forest operations, the operator often handles obstructing trees by reversing the machine along the strip road to gain access to a certain tree (Ovaskainen et al., 2004; Lindroos et al., 2008). In our model, the algorithms presented in Fig. 3 and Fig. 4 are designed to handle such situations. Another way to reduce the time spent reversing the harvester is to use a pivoting outer-boom crane (Lindroos et al., 2008). Full implementation of these factors would probably have further enhanced the benefits of a geometrical harvest pattern (cf. Table III). Some stand factors had unexpectedly significant effects on productivity. Variations in tree species composition are accounted for only as differences in delimbing times in the underlying simulation model. When constructing the regression functions, tree species composition also had a significant effect on TC for other elements, probably due to differences in tree spacing. Based on logical reasoning such relationships were not included in the final regression functions listed in Table V. In the data underlying the presented results, no simulations were excluded on the basis of stem size or stand density, since excluding simulations in certain stands and certain scenarios would make direct comparisons such as those shown in Fig. 8 and Table III irrelevant. However, in practice various scenarios would not be applied in some types of stands, for instance, the $TSRW_{Sel}$ scenario is rarely applied in stands with a mean stem volume below 0.01-0.03 m^3 o.b. in practical forestry, and the $2m^2FF_{Corr}$ and TFF_{Corr} scenarios are primarily designed for stands with mean heights less than 8-10 m. In addition, as many observations as possible were wanted for the regression analyses presented in Table V.

We verified the simulation model continuously during the programming (by comparing model results to manual calculations), and the obtained results were validated by comparing them to three other datasets, with the following outcomes. Firstly, when we used the same model coefficients and reference stands as Eliasson (1999), the model returned results corresponding to Eliasson's findings. Secondly, for $TSRW_{Sel}$, our simulation results were compared to the most commonly used Swedish thinning productivity estimates (Brunberg, 1997). As shown in Fig. 10, there was a mean difference of 3.30 s, possibly at least partly because Brunberg's results probably included time taken for the harvester reversing when trying to avoid obstructing trees. Eliasson (1999) obtained smaller differences when comparing his simulation results to time study material and functions of that time, but his comparisons were based on only six of the 56 stands used in this study. Furthermore, Eliasson compared his results to other, older published time studies than the one used here.

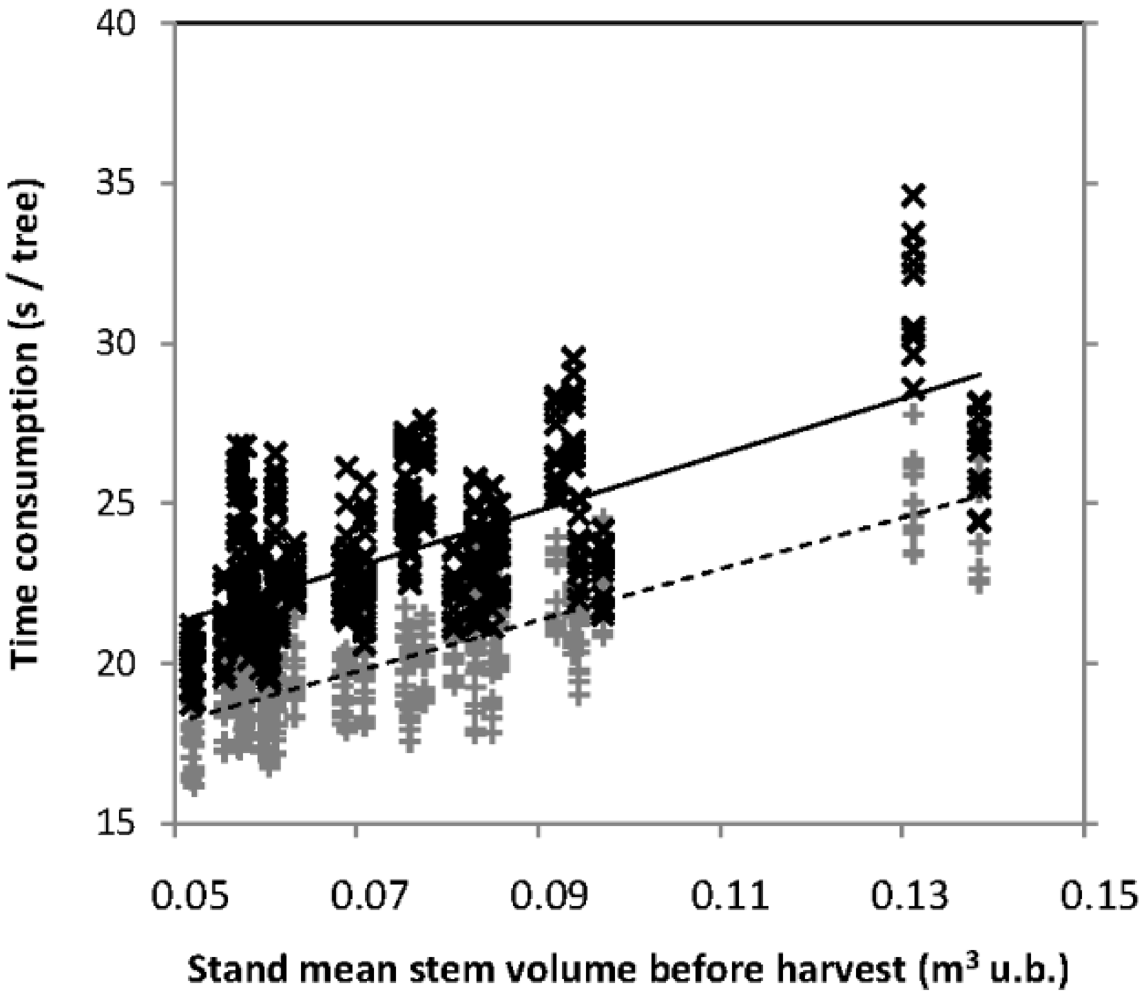


Figure 10. Total harvester productive work time consumption per tree simulated and calculated using functions presented by Brunberg (1997) (_and _, respectively), as a function of stand mean stem volume of stem parts thicker than 5 cm diameter in m3 under bark (u.b.), before harvest. The figure shows the 384 stands with the largest trees, of the total 672 simulations with harvest scenario TSRWSel. The distance between the fitted trend lines averages 3.3 s per tree, equivalent to 14.1% of the average time taken per tree according to the productivity function (Brunberg, 1997).

Finally, for the $TMFF_{Sel}$ scenario, the predicted productivity based on simulations was compared to observed productivity in time studies of similar operations. TC for boom movements, felling and moving (Bergström, 2009) was overestimated by 5.4%, on average, using regression functions based on our simulation results, but less complex than those given in Table V. Comparing processing time to results presented by Bergström (2009) would be irrelevant, since the operation Bergström studied was full tree harvesting, only bunching the full trees at strip road sideTC for processing was instead compared to results obtained in three time studies of more similar operations, in which the butt logs were delimbed (Iwarsson Wide, 2009; Iwarsson Wide & Belbo, 2009; Iwarsson Wide & Belbo, 2010), and was found to be underestimated by 25%. TC should typically be somewhat underestimated in a simulation (cf. Eliasson, 1999), and this could be corrected by adjusting some constants in the simulation model (Table II). The constants could also be adjusted on the basis of new field study results, and thus the accuracy and utility of the simulation model could be further enhanced.

The new harvesting scenarios analyzed in this paper may contribute to more profitable management of young stands, both directly through the increased productivity (as illustrated, for instance, in Table III) and indirectly through addressing some of the key issues regarding thinning in young stands identified by Oikari et al. (2010), e.g. reducing the impact of undergrowth and, if parts of the harvester work cycle are automated (cf. Hellström et al., 2009), the demands on the operator's skills. Recent advances in forest inventory and planning have reduced the costs and increased the utility of tree-level information including spatial information (cf. Holmgren, 2004; Anon., 2010d; Lämås, 2010). Such information may be particularly important for formulating and implementing simulation models such as that presented in this study, which are likely to be used increasingly often, thereby increasing the accuracy of forest management analyses and facilitating the management of forest operations.

The results presented in this study and the above rationale indicate that harvesting in boom-corridors, multiple-tree-handling and the development (and implementation) of area-based felling systems and techniques should increase harvester productivity when thinning dense, young stands by on average 20 – 80% (Table III). The differences between simulated and time study-based productivity (e.g. Fig. 10) suggest that the simulation model presented in this study successfully mimics productivity in real-life forest operations. Hence, productivity for all modeled scenarios should also be fairly accurate, and predictions of productivity using the simulation model or derived regression functions (Table V) should be suitable for comparing the relative merits of diverse harvest scenarios and machine systems for thinning any given stand. Further research efforts could be directed towards quantifying the effects of spatial variation in the stand on harvester productivity, the optimal boom-corridor width, the productivity of the entire supply chain and the effects on stand management of the new machine systems simulated here.

Acknowledgements

The authors wish to thank Sören Holm, Dept. of Forest Resource Management, SLU, Umeå, for helping to construct the models for analysis of variance. We further thank Lars Eliasson and Maria Iwarsson Wide, both at SkogForsk, Uppsala, for providing information regarding various aspects of the simulation model and harvester working techniques. This study was mainly financed by the Brattås Foundation, and partly by the Interreg IV A project Botnia-Atlantica.

References

AedoOrtiz, D. M., Olsen, E. D. & Kellogg, L. D. (1997). Simulating a harvester-forwarder softwood thinning: A software evaluation. *Forest Products Journal, 47*(5), 36-41.

Anon. (2008a). *Log Max 4000B*. (Issue MA 2008/001-JL.) Grangärde: Log Max AB.

Anon. (2008b). *Log Max Accumulation Kit*. (Issue MA 2008/001-JL.) Grangärde: Log Max AB.

Anon. (2010a). *Swedish Statistical Yearbook of Forestry*. Jönköping: Skogsstyrelsen.

Anon. (2010b). *Trädbränsle- och torvpriser 4 / 2010*. Energimyndigheten. [Prices for wood fuel and peat] (In Swedish.)

Anon. (2010c). *Eco Log - Technical specifications*. (Issue MA - 2010/001 - JL.) Söderhamn: Eco Log Sweden AB.

Anon. (2010d). *The Heureka Research Programme. Final Report for Phase 2, October 2005 - September 2009*. SLU.

Asikainen, A. (2010). Simulation of stump crushing and truck transport of chips. *Scandinavian Journal of Forest Research, 25*(3), 245-250.

Bergström, D. (2009). Techniques and Systems for Boom-Corridor Thinning in Young Dense Forests. (Doctoral dissertation, SLU, Umeå) *Acta Universitatis Agriculturae Sueciae, 2009:87*.

Bergström, D., Bergsten, U., Nordfjell, T. & Lundmark, T. (2007). Simulation of geometric thinning systems and their time requirements for young forests. *Silva Fennica, 41*(1), 137-147.

Björheden, R., Apel, K., Shiba, M. & Thompson, M. (1995). *IUFRO forest work study nomenclature*. (Research notes no. 16.) Garpenberg: Swedish University of Agricultural Sciences. Dept. of Operational Efficiency.

Bredberg, C.-J. (1972). *Type stands for the first thinning*. (Research Notes no. 55.) Stockholm: Royal College of Forestry. Dept. of Operational Efficiency. (In Swedish with English summary.)

Brunberg, T. (1997). *Basic data for productivity norms for single-grip harvesters in thinning*. (Redogörelse no. 8.) Uppsala: SkogForsk. (In Swedish with English summary.)

Clark, P. J. & Evans, F. C. (1954). Distance to nearest neighbour as a measure of spatial relationships in populations. *Ecology, 35*, 445-453.

Eliasson, L. (1999). Simulation of thinning with a single-grip harvester. *Forest Science, 45*(1), 26-34.

Eliasson, L. & Lageson, H. (1999). Simulation study of a single-grip harvester in thinning from below and thinning from above. *Scandinavian Journal of Forest Research, 14*(6), 589-595.

di Fulvio, F. (2010). Analysis Of Small Diameter Energy-Wood Harvesting Machinery, Equipment And Systems. (Doctoral dissertation, University of Tuscia, Tuscia) *Department of Technology, Engineering and Science of Environment and Forests, 2010*.

Gullberg, T. (1997). A deductive time consumption model for loading shortwood. *Journal of Forest Engineering, 8*(1), 35-44.

Gustavsson, R. (1974). *Type stands for cleaning*. (Research Note no. 70.) Garpenberg: Royal College of Forestry. Dept. of Operational Efficiency. (In Swedish with English summary.)

Heikkilä, J., Sirén, M., Ahtikoski, A., Hynynen, J., Sauvula, T. & Lehtonen, M. (2009). Energy Wood Thinning as a Part of the Stand Management of Scots Pine and Norway Spruce. *Silva Fennica, 43*(1), 129-146.

Hellström, T., Lärkeryd, P., Nordfjell, T. & Ringdahl, O. (2009). Autonomous forest vehicles: historic, envisioned, and state-of-the-art. *International Journal of Forest Engineering, 20*(1), 31-38.
Holmgren, J. (2004). Prediction of tree height, basal area and stem volume in forest stands using airborne laser scanning. *Scandinavian Journal of Forest Research, 19*(6), 543-553.
Hyytiainen, K., Tahvonen, I. & Valsta, L. (2005). Optimum juvenile density, harvesting, and stand structure in even-aged Scots pine stands. *Forest Science, 51*(2), 120-133.
Iwarsson Wide, M. (2009). *Jämförande studie av olika tekniker för skogsbränsleuttag - Metodstudie - Uttag av massaved, helträd, kombinerat uttag samt knäckkvistning i talldominerat bestånd, Sveaskog, Askersund*. (Arbetsrapport no. 680.) Uppsala: SkogForsk. [A comparative studie of different techniques for forest fuel extraction - Method study - Extraction of pulpwood, whole-trees, combined extraction and rough delimbing in pine dominated stands, Sveaskog, Askersund] (In Swedish.)
Iwarsson Wide, M. & Belbo, H. (2009). *Jämförande studie av olika tekniker för skogsbränsleuttag - Skogsbränsleuttag med Naarva-gripen 1500-40E, Bracke C16.A och LogMax 4000, Mellanskog, Färila*. (Arbetsrapport no. 679.) Uppsala: SkogForsk. [A comparative study of different techniques for forest fuel extraction - Forest fuel extraction with the Naarva 1500-40E grip, Bracke C16.A and LogMax 4000, Mellanskog, Färila] (In Swedish.)
Iwarsson Wide, M. & Belbo, H. (2010). *Jämförande studie av olika tekniker för skogsbränsleuttag i mycket klen skog - Skogsbränsleuttag med Naarva-gripen 1500-40E och Log Max 4000, Mellanskog, Simeå*. (Arbetsrapport no. 709.) Uppsala: SkogForsk. [A comparative study of different techniques for forest fuel extraction in very small forests - Forest fuel extraction with the Naarva 1500-40E grip and LogMax 4000, Mellanskog, Simeå] (In Swedish.)
Jacobson, S., Kukkola, M., Malkonen, E. & Tveite, B. (2000). Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. *Forest Ecology and Management, 129*(1-3), 41-51.
Johansson, J. & Gullberg, T. (2002). Multiple tree handling in the selective felling and bunching of small trees in dense stands. *International Journal of Forest Engineering, 13*(2), 25-34.
Karlsson, L., Bergsten, U., Ulvcrona, T. & Elfving, B. (2011) (submitted). Long-term effects of corridor thinning on growth and yield in young Scots pine (*Pinus sylvestris L.)* stands. Submitted to Scandinavian Journal of Forest Research.
Kuitto, P. J., Keskinen, S., Lindroos, J., Oijala, T., Rajamäki, J., Räsänen, T., et al. (1994). Puutavaran koneellinen hakkuu ja metsäkuljetus. (Metsätehon tiedotus no. 410.): Metsäteho. [Mechanized cutting and forest haulage] (In Finnish with English summary.)Lageson, H. (1997). Effects of thinning type on the harvester productivity and on the residual stand. *Journal of Forest Engineering, 8*(2), 7-14.
Lindroos, O. (2008). The Effects of Increased Mechanization on Time Consumption in Small-Scale Firewood Processing. *Silva Fennica, 42*(5), 791-805.
Lindroos, O., Bergström, D., Johansson, P. & Nordfjell, T. (2008). Cutting corners with a new crane concept. *International Journal of Forest Engineering, 19*(2), 21-27.
Lämås, T. (2010). *The Haglöf PosTex ultrasound instrument for the positioning of objects on forest sample plots*. (Arbetsrapport no. 296.) Umeå: SLU. Inst för skoglig resurshushållning.
Löfroth, C. & Rådström, L. (2006). Allt lägre bränsleförbrukning i skogsbruket. (Resultat no. 3.) Uppsala: SkogForsk. [Fuel consumption continues to fall] (In Swedish.)

Mård, H. (1998). Short-term growth effects of whole-tree harvest in early thinnings of Birch (Betula spp) and Picea abies. *Scandinavian Journal of Forest Research, 13*(3), 317-323.
McNeel, J. F., & Rutherford, D. (1994). Modelling Harvester-Forwarder System Performance in a Selection Harvest. *Journal of Forest Engineering, 6*(1), 7 - 14.
Newnham, R. (1966). A simulation model for studying the effect of stand structure on harvesting pattern. *Forest Chronicle, 42*, 39-44.
Nordfjell, T., Nilsson, P., Henningsson, M. & Wästerlund, I. (2008). Unutilized biomass resources in Swedish young dense forests. In J. Vinterbäck (Ed.), *World Bioenergy 2008* (pp. 323 - 325). Jönköping: The Swedish Bioenergy Association.
Nordlund, S. (1996). Drivningsteknik och metodutveckling i storskogsbruket. (Resultat no. 4.) Uppsala: SkogForsk. [Logging technology and methods: trends in large-scale forestry] (In Swedish.)
Nurminen, T., Korpunen, H. & Uusitalo, J. (2006). Time consumption analysis of the mechanized cut-to-length harvesting system. *Silva Fennica, 40*(2), 335-363.
Nuutinen, Y., Vaatainen, K., Asikainen, A., Prinz, R. & Heinonen, J. (2010). Operational Efficiency and Damage to Sawlogs by Feed Rollers of the Harvester Head. *Silva Fennica, 44*(1), 121-139.
Oikari, M., Karha, K., Palander, T., Pajuoja, H. & Ovaskainen, H. (2010). Analyzing the Views of Wood Harvesting Professionals Related to the Approaches for Increasing the Cost-Efficiency of Wood Harvesting from Young Stands. *Silva Fennica, 44*(3), 481-495.
Ovaskainen, H. (2008). Timber harvester operators working technique in first thinning and the importance of cognitive abilities on work productivity. (Doctoral dissertation, University of Joensuu, Joensuu) *Dissertationes Forestales, 2008:79.*
Ovaskainen, H., Uusitalo, J. & Sassi, T. (2006). Effect of edge trees on harvester positioning in thinning. *Forest Science, 52*(6), 659-669.
Ovaskainen, H., Uusitalo, J. & Vaatainen, K. (2004). Characteristics and significance of a harvester operators' working technique in thinnings. *International Journal of Forest Engineering, 15*(2), 67-77.
Pettersson, N. (1986). *Line thinning in young natural regenerated pine stands*. (Report no. 17.) Garpenberg: Swedish University of Agricultural Sciences. Dept. of Forest Yield Research. (In Swedish with English summary.)
Santesson, M. & Sjunnesson, S. (1972). *Simulation model for thinning machines*. (Research Notes no. 49.) Stockholm: Royal College of Forestry. Dept. of Operational Efficiency.
Spinelli, R. & Visser, R. (2008). Analyzing and estimating delays in harvester operations. *International Journal of Forest Engineering, 19*(1), 36-41.
Talbot, B., Nordfjell, T. & Suadicani, K. (2003). Assessing the utility of two integrated harvester-forwarder machine concepts through stand-level simulation. *International Journal of Forest Engineering, 14*(2), 31-43.
Talbot, B. & Suadicani, K. (2005). Analysis of Two Simulated In-field Chipping and Extraction Systems in Spruce Thinnings. *Biosystems Engineering, 91*(3), 283-292.
Wang, J. X. & Greene, W. D. (1999). An interactive simulation system for modeling stands, harvests, and machines. *International Journal of Forest Engineering, 10*(1), 81-98.
Wang, J. X., LeDoux, C. B. & Li, Y. X. (2005). Simulating cut-to-length harvesting operations in Appalachian hardwoods. *International Journal of Forest Engineering, 16*(2), 11-27.
Varmola, M. & Salminen, H. (2004). Timing and intensity of precommercial thinning in Pinus sylvestris stands. *Scandinavian Journal of Forest Research, 19*(2), 142-151.

Appendix I – algorithms for transforming the type stands to different machine widths

New coordinates (measured in decimeters) for tree i, X_{new_i} and Y_{new_i}, were calculated if it was located beyond one distance between strip roads, $R_{Dist} = \max(X_{new})$, using the function below, where A_T is the area to be transformed, X and Y are vectors with coordinates for all trees in the stand, X_i and Y_i are the old coordinates for tree i, and m_i is the transformation agent (where $\max(m)$ is equivalent to A_T and the number of 1 × 1 dm cells to be transformed in total, and m_i is the rank number of the particular cell containing tree i), defined below.

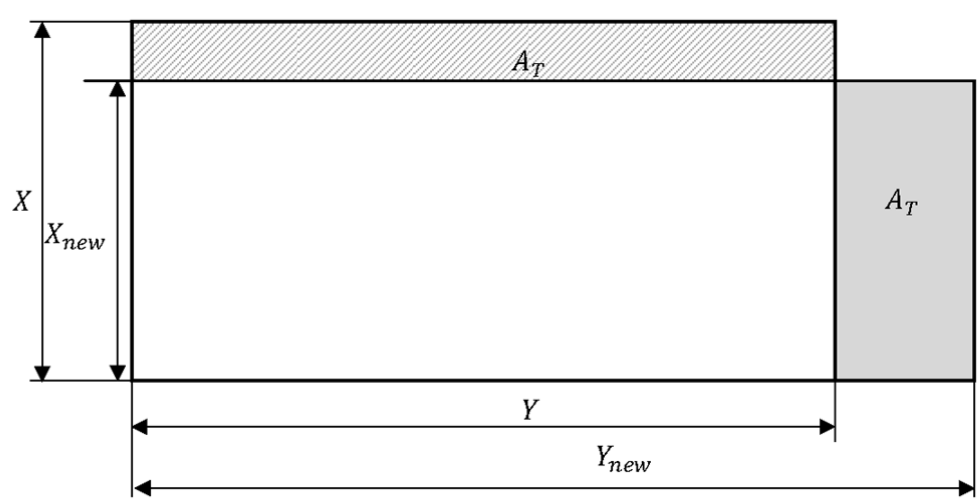
$$A_T = (\max(X) - R_{Dist}) \times \max(Y)$$

$$m_i = (X_i - R_{Dist}) \times \max(Y) + Y_i$$

$$X_{new_i} = \left\| m_i - \left\lfloor \frac{m_i}{R_{Dist}} \right\rfloor \times R_{Dist} \right\|$$

$$Y_{new_i} = \left\| Y_i + m_i - \left\lfloor \frac{m_i}{A_T / R_{Dist}} \right\rfloor \times \frac{A_T}{R_{Dist}} \right\|$$

Some of the concepts are illustrated in the figure below. Other relationships are $X_{new} = R_{Dist}$ and $(X - X_{new}) \times Y = (Y_{new} - Y) \times X$.



Appendix II – Algorithm for tree selection

The algorithm for tree selection used in this study is partly based on subjectively assigned thinning priority numbers available in the dataset. Since these priority numbers favor thinning from below, a guide based on the target thinning ratio was introduced. A random element was used to obtain an even spatial distribution of trees selected for cutting and to mimic real-life harvesting operations, where trees are selected under time pressure and based on incomplete knowledge of tree characteristics. The algorithm is illustrated below.