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Lars Sängstuvall

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Summary

Over recent years, as a result of energy policy at global, European and national levels, the prices and demand for bio-fuel, including forest fuel, have increased. This has lead to reductions in the marginal profits associated with the use of a range of forest fuel assortments. New and improved methods and techniques for extracting logging residues, stumps and whole-trees from young stands are therefore currently being investigated. Unlike final felling, revenues from forest fuel extraction during thinnings are expected to be of about the same magnitude as the revenue from thinning or the cost of pre-commercial thinning. This will probably influence the timing and type of all forest management activities throughout the rotation period of a stand.

When estimating logging potential, forest management is simulated on the basis of assumptions about the forest and the behavior of the forest owner. Priority can be given to forest characteristics, economic or ecological aspects when specifying treatment variables and models can also incorporate probability functions for land owner behavior. Management simulations result in an estimate of the logging potential for the forest area at hand. Forest fuel logging potential is usually derived by appending forest fuel extraction to the roundwood extraction treatments, also taking into account economic and ecological constraints specific for the forest fuel extraction.

In order to estimate the harvestable volume based on economic, ecological and practical criteria we must have some measures of the properties and influence of these criteria. This essay reviews productivity studies that could be of use when modeling thinning and forest fuel operations in Swedish forests. Furthermore it pinpoints areas of insufficient knowledge with respect to the productivity of forest fuel extraction from young forests.

In the case of such young stands, there is practically no information about land owner behavior, and any logging potential estimates would currently have to rely on some kind of simulation based on a specific forest management goal. Assuming that forest fuel extraction affects forest management, the accuracy of estimates would be improved if such operations were modeled accurately and fully incorporated into the ordinary logging potential estimate.

Comparative and correlation time studies are commonly used in forestry to evaluate the performance of different systems or techniques or to evaluate and price different working units within a system or technique. For roundwood logging, both the single-grip harvester and the forwarder are established technological systems, and hence there are many correlation time studies quantifying time consumption in different working environments for these systems. Whole-tree or tree-section logging, particularly in young forests, has been little used in Nordic forestry and hence most time studies that are available are comparative. The properties and influence of forest fuel harvesting in young stands therefore needs to be further investigated. This will ensure appropriate estimates of the amount of forest fuel that can be derived from young stands and will facilitate long-term forest management planning with forest fuel extraction included as a treatment.

Harvesting productivity, expressed as number of trees processed per time unit, decreases with increasing tree size and for more processed, e.g. delimbed, assortments. Forest haulage productivity decreases with, among other variables, increasing transportation distance, decreasing load size, and decreasing grapple size.

A theoretical, partially deductive, framework for the time associated with forwarding has been adapted to the specific environments described in a number of studies. Comparing the calculated time consumptions with the actual results from the studies shows that the theoretically-based time consumption model has a high level of accuracy. This indicates that the time consumption for forwarding under defined working conditions (e.g. pile size, proportion of solid volume) not yet studied or experienced can be modeled in advance with acceptable accuracy. A few questions still remain with respect to the way to adapt the theoretical model to specific situations, since different approaches seemed more or less successful in different cases.

Contents

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Introduction

Over recent years, as a result of energy policy at global, European and national levels (Anon., 2010c), the prices and demand for bio-fuel have increased (Anon., 2009). This has lead to increasing use of different forest fuel assortments and decreasing marginal profits associated with forest fuel extraction (Lönner *et al.*, 1998; Athanassiadis *et al.*, 2009). There has, therefore, been increasing research and development aimed at identifying more efficient and cost-effective techniques and systems for extraction, involving new and improved approaches to extracting logging residues, stumps and whole-trees from young stands (e.g. Bergström, 2009).

Forest fuels have traditionally been considered a by-product in the Swedish forestry. Extraction of forest fuels is usually an add-on to the ordinary silvicultural activities generating roundwood. This is the case when a positive net revenue is expected from the forest fuel extraction and when ecological restrictions regarding e.g. nutrient removal (Jacobson *et al.*, 2000; Luiro *et al.*, 2010) have been taken into account. As long as these criteria are used for deciding when and where to extract forest fuels, estimating the potential forest fuel harvest is simply a function of the potential roundwood harvest and the economic and ecological constraints on forest fuel extraction. This method is typically used in studies of available forest fuel, such as that by Athanassiadis *et al.* (2009) assessing potential volumes of logging residues and stumps at final felling.

Forest management planning

Forest management decisions are often based on analyses of the forest owner's goals. After goal identification, a range of possible forest management alternatives are formulated (e.g. Bettinger *et al.*, 2009). Two approaches are available to create plans for forest management that fulfill these goals. Either forest development are modeled as a function of predefined forest management activities, resulting in projections of future forest states answering the question *"What if we manage this forest in this particular way?"*. Influence of logging operations productivity may here be included in the formulation of predefined forest management guidelines, and not considered in the analysis itself. Alternatively, a large number of parallel forest management programs can be simulated, and the program that best fulfils the landowner's goals is then selected (cf. Bettinger *et al.*, 2009). This optimization approach can be said to answer the question *"How to manage the forest to achieve maximum output of our preferred utilities?"*. Here, since the productivity of logging operations affects costs and thus net revenue, functions describing this are included in the analysis.

When only one goal at a time is considered, the optimization approach can be said to result in a benchmark which any simulation approach results at the best may be equivalent with. Both approaches can handle e.g. ecological restrictions to forest management (e.g. Fries & Lämås, 2000), but the optimization approach selects the forest management program that has the highest goal fulfillment given that the restrictions are met. Furthermore, an optimization approach allows for multiple goals to be assessed at the same time, and criteria that would otherwise have been handled as restrictions can be incorporated as goals in e.g. goal programming (cf. Bettinger *et al.*, 2009). A common goal in Swedish forestry is to maximize the net present value of timber harvest, perhaps under different constraints with respect to nature conservation, even flow of timber and cash or the future state of the forest. Other goals are however also imaginable. The Heureka system (Anon., 2010d) is a powerful tool for performing this planning process. The result of such analysis may be a stand-level treatment program with suggested timings for and types of management activities, for example pre-commercial thinning, thinning and final felling, throughout the rotation period of a stand. The sum of in- and outputs from all stand-level treatment programs in any time period is equivalent to e.g. the total amount of machine work needed or the logging potential for that forest and time period.

Forest management planning in large forestry companies in Sweden is typically performed according to one of the principles above (Söderholm, 2002). Optimization using the Forest Management Planning Package (Jonsson *et al.*, 1993) or, more recently, Heureka PlanWise (Anon., 2010d) is common, although some major forestry companies use simulation approaches with tools such as Hugin (Lundström & Söderberg, 1996). These decision support systems utilize logging operation productivity functions to calculate harvesting costs for different forest management activities, e.g. the new Heureka system uses SkogForsk's productivity functions (Brunberg, 1995; 1997; 2004).

Logging potential estimates

Roundwood logging potential

In 2008, the Swedish Forest Agency published their latest estimate of logging potential in Sweden, known as SKA-08 (Skogsstyrelsen, 2008). The main focus of SKA-08 is on roundwood potential; it includes a number of cutting scenarios for the entire Swedish forestry sector, modeled over 100 years using the Hugin system (Lundström & Söderberg, 1996). Predictions of growth and yield are made at the plot level using about 31 000 inventory plots measured during the five-year period between 2002 and 2006 as part of the Swedish NFI (National Forest Inventory); this interval represents the normal cycle for revisiting permanent plots (SLU, 2007). Treatments are assigned to each plot using priority functions based on either percent volume growth or probability functions (Holm & Lundström, 2000). The total amount of harvesting to be performed in a ten-year period is determined based on the state of the forest in the previous period and assumptions and restrictions focusing on non-declining volume growth and maintaining the forest in a state similar to that recorded at the outset.

Regardless of which method is used for ranking the plots, some plots are always assigned to less prioritized treatments, and some plots are also not treated although they are highly prioritized with respect to a particular treatment. These exceptions are included in order to mimic the real-life diversity in the goals of landowners, to mimic the non-optimal behavior that occurs even though the goals and plans to achieve them are known and to take into account the fact that treatment prioritization in the system occurs at the plot level, whereas treatment decisions in practical forestry are usually taken on the basis of stand-level means of variables (Skogsstyrelsen, 2008). It is likely that the next national estimate of logging potential will use Heureka RegWise (Anon., 2010d) as a tool. The principles associated with prioritizing treatments on the plot level according to either land owner behavior, volume growth percent or a combination of forest and land owner characteristics (Eriksson, 2008) will however still be the same, and it is less likely that an optimization approach will be used.

In Finland the MELA optimization system is used for estimating long-term logging potential at the national level (Siitonen, 1996; Siitonen & Nuutinen, 1996; Anon., 2008). This is a great difference towards Sweden, where long-term forecasts for logging at a national level are usually produced using pure simulation tools without optimization, as described above. The Swedish approach to dealing with non-optimal behavior of landowners, i.e. using probabilities and assigning plots to treatments other than the most highly prioritized one, has its counterpart in the Finnish use of analytical hierarchy processes (Pesonen, 2001) when formulating the cutting scenarios underlying the optimizations. Both methods leads to harvest potential estimations somewhat below the benchmark.

In countries or regions with less developed models and perhaps a less well established forestry sector, accurate information about forests may be poor or missing. In such cases, a stage-structured model for growth and yield prediction, such as the IIASA-model, later renamed EFISCEN (Sallnäs, 1996), may be used. EFISCEN is also used in very large-scale projects like EUWOOD and other projects at the EFI (Anon., 2010b).

Forest fuel logging potential

In Sweden the most recent estimates of forest fuel potential were made in SKA-08 (Skogsstyrelsen, 2008). In SKA-08, only ecological and technical restrictions on forest fuel extraction are considered. Economically infeasible treatments are therefore still included in the forest fuel potentials in SKA-08. Therefore, the results from SKA-08 were further analyzed by Athanassiadis *et al.* (2009) in terms of marginal costs for extraction. In their study however, forest fuel extraction is only appended to roundwood extraction or pre-commercial thinning and is not considered as a treatment in its own right. The methodology used in SKA-08 has also been used at the regional level within Sweden, for example by the Forest Agency in Dalarna and Gävleborg (Ingebro, 2006).

The sophisticated methodology, including the probability of treatments being applied, used in SKA-08 is hard to model for a treatment that is not yet known or well-established among forest owners. Studies by Bohlin & Roos (2002) and Norin & Tosterud (2009) show that the majority of Swedish forest owners have a positive attitude towards logging residue extraction during final fellings. In Finland subsidies are used to mobilize land owners into harvesting forest fuel in young stands, because market economics do not encourage it (Heikkila *et al.*, 2007; Ahtikoski *et al.*, 2008; Petty & Kärhä, 2008).

In a Swedish study Nordfjell *et al.* (2008) estimated the forest fuel available from young dense forests in Sweden based on NFI data and assumptions about which forests were suitable for forest fuel extraction. All previously unthinned permanent plots suitable for thinning as the next management activity, measured in the NFI in the five-year period between 2001 and 2005, are considered. Out of these, all plots with a standing biomass of at least 30 tons of dry matter per hectare and with a dominant height (expressed as mean height of the 2 thickest trees within a plot with a 10 m radius) below 12 m are considered suitable for forest fuel extraction. The total number of plots fitting these criteria is then divided into yearly amounts. A 50% biomass extraction rate is assumed in all plots subjected to extraction.

Vainio *et al.* (2009) investigates the potential of logging residues in first thinnings in an area in western Finland and finds high forest fuel potential, even under economic constraints. They use permanent field sample plots and forest management plans to model an entire forest landscape in the region, and then investigate the need for thinning according to existing management guidelines. Thus, the forest fuel extraction is appended to the roundwood extraction decision, and only performed when it yielded a positive net income. Appending forest fuel extraction to roundwood management activities is a method also used in Estonia (Padari *et al.*, 2009). On a larger scale, the same approach is used with EFISCEN as a tool (Anon., 2006).

In a Finnish study by Malinen *et al.* (2001) forest fuel potential is assessed at a regional level through incorporating it into the simulation and selection of management actions. The results indicate that extraction of logging residues in final fellings is far more profitable than extracting forest fuel from young dense stands. Furthermore the price of forest fuel at that time resulted in a low level of economically viable extraction, and an increase in price of 20% lead to an increase in extraction of ~250%. It is reasonable to believe that a similar analysis performed with the forest fuel price levels of today would give an even higher increase in extraction.

The Finnish study (Malinen *et al.*, 2001) along with the study by Nordfjell *et al.* (2008) are the only two examples identified that do not append forest fuel extraction to roundwood management actions, but consider forest fuel extraction as a treatment in its own right. In the Finnish study, forest fuel extraction from young stands is incorporated into the ordinary forest management program whereas in the Swedish study the forest fuel extraction is independent of other forest management actions. Thus, in the Swedish case the results of Nordfjell *et al.* (2008) cannot simply be considered as a add-on to the ordinary logging potential, but rather as a trade-off with ordinary thinning, perhaps foregone by clearance of undergrowth. In all other studies, including Malinen *et al.* (2001) the results apart from stemwood volume can be considered as an add-on to roundwood felling.

With constantly improving remote sensing techniques, new approaches to estimating logging potential in general and forest fuel potential in particular have been examined. Bååth *et al.* (2002) used satellite data to impute field-measured plot data to entire forest areas, then used the Hugin system to calculate logging potential and finally appended forest fuel to roundwood extraction. Kotamaa *et al.* (2010) used combined data from an airborne laser scanner and aerial photographs and compared plotwise silvicultural treatment suggestions from remote sensing with treatment suggestions based on a field inventory. The method used failed to identify the few plots, 4 out of 463, suitable for energy-wood thinning, and furthermore had a high RMSE for predicting biomass in forests to be thinned.

Problem definition and objectives

If forest fuel extraction is appended to ordinary forest management without altering the timing or management type there is a risk that the total net present value, or other measure of goal achievement, will not be optimal and could have been higher if a different timing or type of roundwood harvest had been selected. However, in final fellings the revenue from roundwood harvest is several orders of magnitude greater than the revenue from forest fuel extraction. Furthermore, the limits (e.g., minimum sawlog diameter) between the three assortment groups sawlogs, pulpwood and forest fuels in final fellings have until now often also reflected the best economic use of the parts of a tree with a particular diameter and wood quality (e.g. Sallin, 2008). This indicates that forest fuel extraction during final fellings will only have a minor effect on the timing and type of management activities even if fully incorporated into the analysis and planning of forestry activities.

In stands at an appropriate age for pre-commercial thinning or first thinning the possible revenue from forest fuel extraction is about the same magnitude as the revenue from thinning or the cost of pre-commercial thinning. In addition, several economic analyses of thinning alternatives in young dense forests with small diameter stems have indicated that a forest fuel harvest returns a higher revenue than pulpwood harvest, even if the trees of pulpwood dimension are used for forest fuel (Gullberg, 2000; Liss, 2004; Nilsson, 2009). This suggests that forest fuel extraction in early thinnings will have a major effect on the time and type of management actions when fully incorporated into the analysis and planning of forestry at the stand-, forest- and national levels.

To estimate the harvestable volume based on economic, ecological and technical criteria the properties and influence of these criteria must be known. Furthermore, it is likely that the optimal management with respect to timing and types of pre-commercial and first thinnings would differ significantly from current practices. Therefore, a more accurate approach to estimating the true potential of forest fuel from early thinnings would be to include this treatment in the planning or scenario analysis process rather than to append it to a forest management plan based on roundwood revenues. If such an approach is used, knowledge of productivity and costs in a new operation like forest fuel extraction in young stands is of even greater importance.

The aims of this paper are:

I) to explore previous studies in the field of logging equipment productivity, including both simulations and time studies, relating to forest operations in Nordic conditions with a focus on young stands and forest fuel extraction;

II) to gather information on productivity functions necessary for forest management planning, including estimating potential forest fuel from early thinnings and;

III) to identify any missing knowledge needed to perform the analysis in II).

In addition, production of this paper is intended to increase the author's knowledge of subjects related to his PhD project and to provide him with experience of scientific information retrieval and writing. As a result of this complementary objective, the paper may not be as clearly focused as might be expected.

Materials and methods

The study was conducted in the form of a literature review using web-based search engines (Web of Knowledge, LUKAS) plus the reference lists of all publications that were consulted during the review. The research started with a keyword search, for example using the search term

“forest and producti* and simulat* and (felling OR harvester) not (crop OR agri*)”.*

Interesting hits were then used when searching through citations or related records. Newer and geographically closer publications were prioritized over older and more distant studies. In addition, personal communications with colleagues in the Department of Forest Resource Management provided new ideas and new approaches.

Review of logging equipment productivity

Work studies in forestry often focus on productivity, defined as the ratio between input and output of a system. The input often consists of working time for employees or machines, so time studies are a well-known concept. There are two different kinds of time studies: comparative and correlation. In comparative studies, environmental factors are kept constant to evaluate different working techniques, systems or methods compared to others. This type of time study is usually performed quite early in the life-cycle of a technique, system or method. In correlation studies, the effects of different influencing factors are examined using the same methods, systems or techniques. This type of time study is often performed during later stages in the life-cycle e.g. to serve as a base for a fair and general piece-rate-based salary system. Throughout the history of forestry and forest research, since work studies first were applied in the 1930s, an enormous number of both types have been performed and reported. (Samset, 1990; Samset, 1992)

A time study or work study in forestry typically measures the time consumption per output unit divided on the basis of different work elements. The time consumption is measured either continuously or using the work-sampling method (Eliasson, 1998). In a correlation time study, regression analysis is then usually used to describe relationships between dependent and independent variables.

Felling, processing and cutting devices

Different ways to separate the tree from the stump have been tested; these have involved both different approaches to placement of the cutting device (boom-tip or machine mounted) and different cutting principles (Malmberg, 1981). The more common principles, including saw chain and cutting/slicing devices, have been reviewed by e.g. Brunberg (1998) and Iwarsson Wide (2009a). A range of circular cutting heads (Ligné *et al.*, 2005; Anon., 2010a) employing either saw chains or cutting techniques have also been developed and tested. Delimbing, debarking and bucking have been carried out in the forest, at landing or at the plant (Dahlin, 1991; Ager, 2010). However, a delimbed and debarked log is usually the final product, ready to be transformed into sawnwood or pulp.

When using wood for energy production, the final product is biomass ready to be transformed into energy, regardless of the part of the tree from which it originated. Therefore, extraction of not only stemwood but also stumps, branches, tops, needles and bark contributes to the total amount of forest fuel harvested. However, removing too many needles and fine branches from the forest may adversely affect subsequent tree growth due to nutrient deficit (Egnell & Leijon, 1997; Mård, 1998; Jacobson *et al.*, 2000; Luiro *et al.*, 2010). In addition, a large proportion of tops and branches in the harvested assortment may lead to lower load density (Nordfjell & Liss, 2000), resulting in lower productivity in off- and on-road transport (e.g. Gullberg, 1997b).

Single-grip harvester; properties and productivity estimates

Since the beginning of the 1990s, single-grip harvesters have gained status as the dominant harvesting technology in Swedish forestry (Nordlund, 1996; Löfroth & Rådström, 2006). The introduction of the single-grip harvester was a giant technological leap in forestry productivity, especially during thinning operations, in the Nordic countries. Since its original introduction, all technological improvements to the harvesting machinery have resulted in small additional increases in productivity.

Samset (1990) in his “Law of discontinuous evolution” lists four stages associated with the usual development of a working method or technology. In stage 1, the economic pressure stage, the operating costs of the old method increase more than productivity. In stage 2, the development stage, new methods are sought. In stage 3, the introduction stage, a new method is introduced onto the market. In stage 4, the stabilizing stage, the new method becomes fully integrated into the work area. The single-grip harvester handling individual trees can be said to be somewhere between stages 4, 1 and 2, depending on geography and type of felling operation considered. New methods, systems and techniques are being investigated, e.g. continuous felling of small trees as modeled by Bergström *et al.* (2007). Other interesting techniques under investigation are multiple tree handling felling heads (Bredberg & Moberg, 1971; Johansson & Gullberg, 2002; Bergkvist, 2003; Kärhä, 2006; Ovaskainen *et al.*, 2008) and pivoting outer boom cranes (Lindroos *et al.*, 2008).

The output of a single-grip harvester is usually roundwood, delimbed and bucked into logs. A single-grip harvester can however produce tree sections or whole trees with no or only minor modifications; for example, by using rounded delimbing knives instead of sharpened ones (Iwarsson Wide, 2009b), producing a rough-delimbed log assortment. A large number of productivity studies have been performed on single-grip harvesters and some of them, focusing on thinning, are discussed in the text, listed in Table 1 and reviewed graphically in Figure 1.

Currently, the most commonly used harvester productivity models in Sweden are the different functions by Brunberg (1995; 1997). These are based on a vast set of material gathered from a large number of time studies and experiments, not specifically intended to be used as the basis for productivity estimates or productivity norms. The underlying material however has a broad span of characteristics with respect to independent variables that affect harvester productivity, since much of it was derived from correlation studies focusing on e.g. different thinning forms. This makes it suitable for using as material upon which to base general productivity norms.

A similar set of functions, based on a wide range of material collected in Finland, are presented by Kuitto *et al.* (1994). Since no large-scale time studies of the mechanized cut to length-system had been published in Finland or Sweden for about ten years, Nurminen *et al.* (2006) undertook such a time study and derived time consumption equations in order to generate updated functions based on newer technology and working methods. Additional Finnish studies on the productivity of thinning harvesters include a time study on small thinning harvesters (Kärhä *et al.*, 2004) and a follow up study, also on small thinning harvesters (Siren & Aaltio, 2003). In North America, Kellogg & Bettinger (1994) and McNeel & Rutherford (1994) investigated the performance of harvester-forwarder systems in thinnings and selection harvests and produced results similar to the Nordic studies.

Eliasson (1998) reviewed most of the studies examining single-grip harvesters up to that date. He concluded that, apart from tree size, there are poor and contradictory results relating to the factors influencing single-grip harvester productivity. Research after that date has provided little new information on the subject (Table 1).

Whole-tree or tree section logging

During the final "glory days" of tree section harvesting in Sweden, tree sections of pulpwood dimensions were extracted and taken to terminals were delimbing and debarking took place. Branches and bark were utilized as bio-fuel, but the stemwood was used for pulp. Due to changes in pulp and pulpwood quality demands, energy prices and lagging technical development, the tree section system for pulpwood procurement became uneconomic (Hillring, 1996). Much research within the area of whole-tree or tree section harvesting comes from that period, from the 1980s to the mid-90s. From the mid-90s, tree-sections and whole-trees are almost only used for energy purposes. Hereafter, the term 'whole-trees' will be used to describe these units.

Productivity studies of harvesting whole-trees are seldom as comprehensive as those for roundwood. Because whole-tree harvesting never has been a major component of Nordic forestry, the technology has never fully matured into the stabilizing stage 4 according to the law of discontinuous evolution (Samset, 1990). As a consequence of this many of the productivity studies are comparative time studies or simulations, comparing e.g. different cutting devices in a certain environment (Kärhä, 2006). The results of these studies are sometimes presented as time consumption for the study object only, without any time consumption model (Liss, 1999; Liss, 2004; Bergström *et al.*, 2007; Jylhä & Laitila, 2007; Bergström, 2009; Nilsson, 2009). Hence, these studies are not included in Table 1 since no independent variables affecting productivity are presented. Selected results are however included in Figure 1. For those productivity studies on whole-tree felling that do include productivity functions (Moberg, 1991; Gullberg, 2000; Kärhä *et al.*, 2005; Spinelli *et al.*, 2007; Pan *et al.*, 2008; Fulvio, 2010), the independent variables are presented in Table 1.

Without claiming to have covered all published studies of the productivity of whole-tree harvesting from young stands, there is a clear tendency for there to be fewer independent variables associated with whole-tree harvesting than roundwood harvesting (see Table 1).

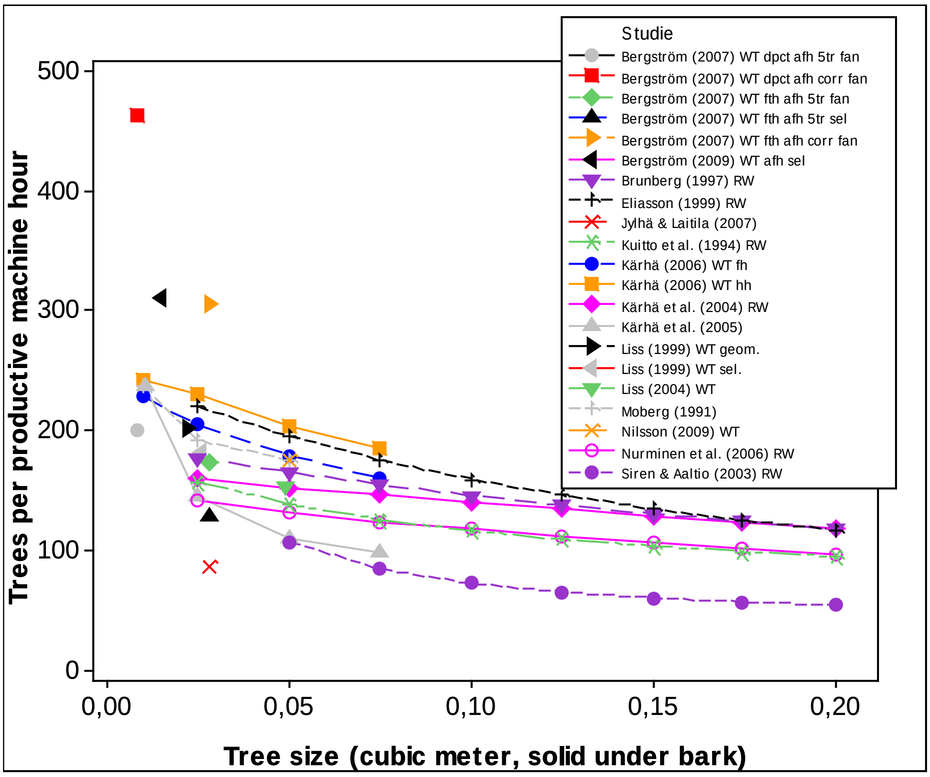

Figure 1. Synthesis of productivity estimates and results from time studies and simulations for different harvesting techniques and machines. Productivity on the y-axis and tree size on the x-axis. Wherever the underlying models have allowed, the independent variables are the same in the different models. Otherwise, the parameter values and environmental configuration presented in each of the papers have been maintained. For a list of settings, assumptions and adaptions see Appendix I. WT means whole-trees and RW means roundwood. Other abbreviations are explained in Appendix I, but are mainly for use when consulting the original publications to distinguish which results have been selected for display here.

A number of points arise from Figure 1. First, the only follow-up study, undertaken by Sirén & Aaltio (2003), exhibited considerably lower productivity than the time studies or simulations. The difference between this and the function presented by Kärhä *et al.* (2004), which was derived using some of the same machines as in the study by Sirén & Aaltio, is particularly noteworthy. This hints at the "study effect" (Samset, 1992), first discovered in the Hawthorne-experiments (Landsberger, 1958) and widely known in work science. The result is that an operator may increase productivity when being studied although the work environment has not been altered. Furthermore, an unusually low conversion factor between E_{15}-time and E_0-time (productive machine time with and without stops lasting up to 15 minutes, respectively) is presented and used by Sirén & Aaltio (2003).

The reader should also consider that the outputs (products) of the different works described in Figure 1 are not the same. The different output assortments at strip-road side for the studies in Figure 1 are given in Table 1 and Appendix I. For example, whole-tree harvesting (e.g. Kärhä (2006), Moberg (1991)) generally results in higher productivity expressed in trees per unit time than roundwood harvesting. The most obvious exception is the low productivity for whole-tree harvesting in the study by Kärhä *et al.* (2005). This was a comparative study using only a cutting felling head with different base machines and in which the driver had limited experience – from less than a week to a few months – working with the cutting head. Another exception is the high productivity for roundwood harvesting in the study by Eliasson (1999). In this case, rare work elements were not included in the simulation model, which may explain part of the overestimate of productivity.

It is also noteworthy that motor-manual felling and piling, as in the study by Moberg (1991), competes effectively with mechanized harvesting, not only in terms of cost but also in terms of productivity. This concurs with productivity research into pre-commercial thinning (Ligné *et al.*, 2005), in which motor-manual work has been found to be both more effective and has a lower cost per time unit than mechanized work. Productivity that is about equal to that achieved by motor-manual felling may in fact be a general problem associated with selective mechanized felling of trees, since the processing time for whole-tree harvesting is very low as long as the trees are small and easy to pile. Thus, one interesting approach to increasing productivity in whole-tree harvesting is to abandon the selective harvesting principle used in most of the studies included in Figure 1 in favor of a geometric working pattern. Such an approach may increase productivity by 16 to 40% (Bergström *et al.*, 2007; Bergström, 2009). Although the effect of tree size on time consumption and productivity seems to be almost the only thing that the productivity studies have in common, there is one exception in Table 1. In a North American time study undertaken by Pan *et al.* (2008) tree size does not have a significant effect of time consumption per working cycle. However, if tree size increases then the volume harvested per work cycle also increases, so productivity in terms of volume per time depends on tree size also in this study. The lack of effect of tree size on time consumption per work cycle is explained by the small tree sizes and high machine performance. Independent variables used in the study by Pan *et al.* (2008) were, instead, variables such as distances between trees, piles and machine positions. These variables are also some of the most important model parameters in Eliasson’s (1999) simulation models.

Bergström (2009) showed that tree size does not affect the felling time during continuous felling of small trees when using a boom-tip mounted felling device moving perpendicular to the base machine. However, if the boom along a fixed radius from the base machine, felling speed increases and tree size in fact becomes limiting to felling time consumption. In Bergström’s (2009) study the base machine working speed is the limiting factor, and it is likely that the same was true for Pan *et al.*’s (2008) results. Since the individual distances between trees, pile positions and the machine are usually not known it may be difficult to apply to the functions generated by Pan *et al.* (2008). However, if the cutting removal perpendicular distance to the strip road is evenly distributed, then the mean distance between tree and machine should be easy to derive from the distance between the strip roads, the strip road width and the distance between machine positions.

Table 1. Productivity functions for felling and, where appropriate, delimbing and bucking. Independent variables in the productivity functions are presented to give an indication of the level of detail and general applicability of the functions. See also Appendix I for further information on some of the functions.

					Independent variables										
Study, function	Data source	Felling device	Assortment at striproad side	Dependent variable	Tree size	Distance machine-tree-pile	Multiple tree handling	Tree species	Strip road width	Speed + terrain	Thinning method	Removal	Residual stand	Distance between machine positions	Machine brand
Brunberg 1997	Time studies	Single-grip harvester	Roundwood	Time per tree unit	X			X	X	X	X	X	X		
Kuitto et al. 1994	Time studies	Single-grip harvester	Roundwood	Volume per time unit	X					X		X			
Nurminen et al. 2006	Time studies	Single-grip harvester	Roundwood	Time per tree unit	X			X							
Kärhä et al. 2004	Time studies	Single-grip harvester	Roundwood	Volume per time unit	X						X				X
Kellog & Bettinger 1994	Time studies	Single-grip harvester	Roundwood	Volume per time unit	X										
McNeel & Rutherford 1994	Time studies	Single-grip harvester	Roundwood	Time per tree unit	X									X	
Siren & Aaltio 2003	Follow-up study	Single-grip harvester	Roundwood	Volume per time unit	X										X
Eliasson 1999	Simulation	Single-grip harvester	Roundwood	Time per tree unit	X							X		X	
Moberg 1991	Time studies	Motor-manual	Whole-trees	Mass per time unit	X				X						
Gullberg 2000	Time studies	Feller-buncher	Whole-trees	Trees per time unit	X							X			
Kärhä 2005	Time studies	Feller-buncher	Tree sections	Volume per time unit	X										
Spinelli et al. 2007	Time studies	Feller-buncher	Whole-trees	Mass per time unit	X										
Pan et al. 2008	Time studies	Feller-buncher	Whole-trees	Time per work cycle		X	X							X	
di Fulvio 2010	Time studies	Feller-buncher	Whole-trees	Volume per time unit	X										

Forest haulage productivity estimates

Ever since mechanization began in the 1950s, forest haulage in the Nordic countries has been performed, to some extent, using forwarders, and since the mid-60s machines have performed the majority of the forest haulage work in Sweden. Flexibility, better wood hygiene, economy, reduced ground damage and better integration with existing transport systems are some of the main arguments for using forwarders instead of skidders (Salminen, 1983). Hence, this review focuses entirely on forwarding productivity. This section first reviews a number of inductive time consumption or productivity models for forest haulage, and then presents the principles of a partially deductive time consumption model.

An inductive approach means measuring the time consumption for different work elements and afterwards trying to correlate differences in time consumption with independent variables in the system. A deductive approach on the other hand means that the work elements are analyzed on theoretical grounds, identifying the independent variables that affect time consumption for a specific work element. Coefficients for those independent variables are then either estimated or measured in empirical studies.

A selection of inductive time consumption studies

The most frequently used productivity models for roundwood forwarding in Sweden are those by Brunberg (2004). The corresponding Finnish models were produced by Kuitto *et al.* (1994). As in the case of harvesting, a new study was undertaken by Nurminen *et al.* (2006) to explore whether productivity in Finnish forest haulage had increased since Kuitto *et al.*'s (1994) study. The independent variables used in these models are presented in Table 2. As with harvesting, the maturity of the forwarder technology resulted in all studies being correlative and incorporating a large number of independent variables.

Even productivity models based on small data sets may include many independent variables (e.g. Nurminen *et al.*, 2006). Because so many relationships are known between the factors affecting roundwood forwarding time (Gullberg, 1997b), it is easy to identify variables to include in a forwarder productivity model. Forwarding of logging residues and whole-trees is less well represented in the research. For the forwarding of logging residues, few factors are known to affect productivity, and as a consequence many companies in Sweden still calculate the cost of forwarding logging residues on the basis of time (Johannesson, 2010). Nurmi (2007) found that, when considered as a single independent variable, forwarding distance (one of the most important factors in productivity models of roundwood haulage) did not have a significant impact on the productivity of logging residue haulage. However, if load size was also included in the model, forwarding distance was significant.

Forwarding of whole-trees and bundles has been investigated in a number of Finnish studies (e.g. Kärhä, 2006; Laitila *et al.*, 2007; Laitila *et al.*, 2009). In these models, presented in Table 2, several independent variables have been included, suggesting that forwarding of whole-trees is easier to describe than forwarding of logging residues. Some of the productivity functions in the studies mentioned above are represented graphically in Figure 2.

Table 2. Productivity functions for forest haulage. Independent variables used in the productivity functions are presented to give an indication of the level of detail and general applicability of the functions.

					Independent variables										
Study, function	Data source	Transportation device	Assortment at striproad side	Dependent variable	Transportation distance	Pile availability	Pile volume	Removal (+strip road width)	Machine size	Speed + terrain	Load size	Grapple size	Assortment(s)	Distance between machine positions	
Brunberg 2004	Time studies	Forwarder	Roundwood	Time per unit volume	X			X	X	X	X		X		
Kuitto et al. 1994	Time studies	Forwarder	Roundwood	Time per unit volume	X			X	X	X	X	X			
Nurminen et al. 2006	Time studies	Forwarder	Roundwood	Time per unit volume	X			X		X	X		X		
Talbot et al. 2003	Simulation	Forwarder	Roundwood	Time per unit volume	X			X							
Gullberg 1997	Deductive + literature review	Forwarder	(Roundwood)	Time per unit volume	X	X	X	X	X	X	X	X	X	X	(other, see Appendix III)
Laitila 2007	Time studies	Forwarder	Whole-trees	Time per unit volume	X		X	X			X	X		X	
Laitila et al. 2009	Time studies	Forwarder	Bundles	Time per unit volume	X			X			X				
Nurmi 2007	Time studies	Forwarder	Logging residues	Mass per time unit	X						X				

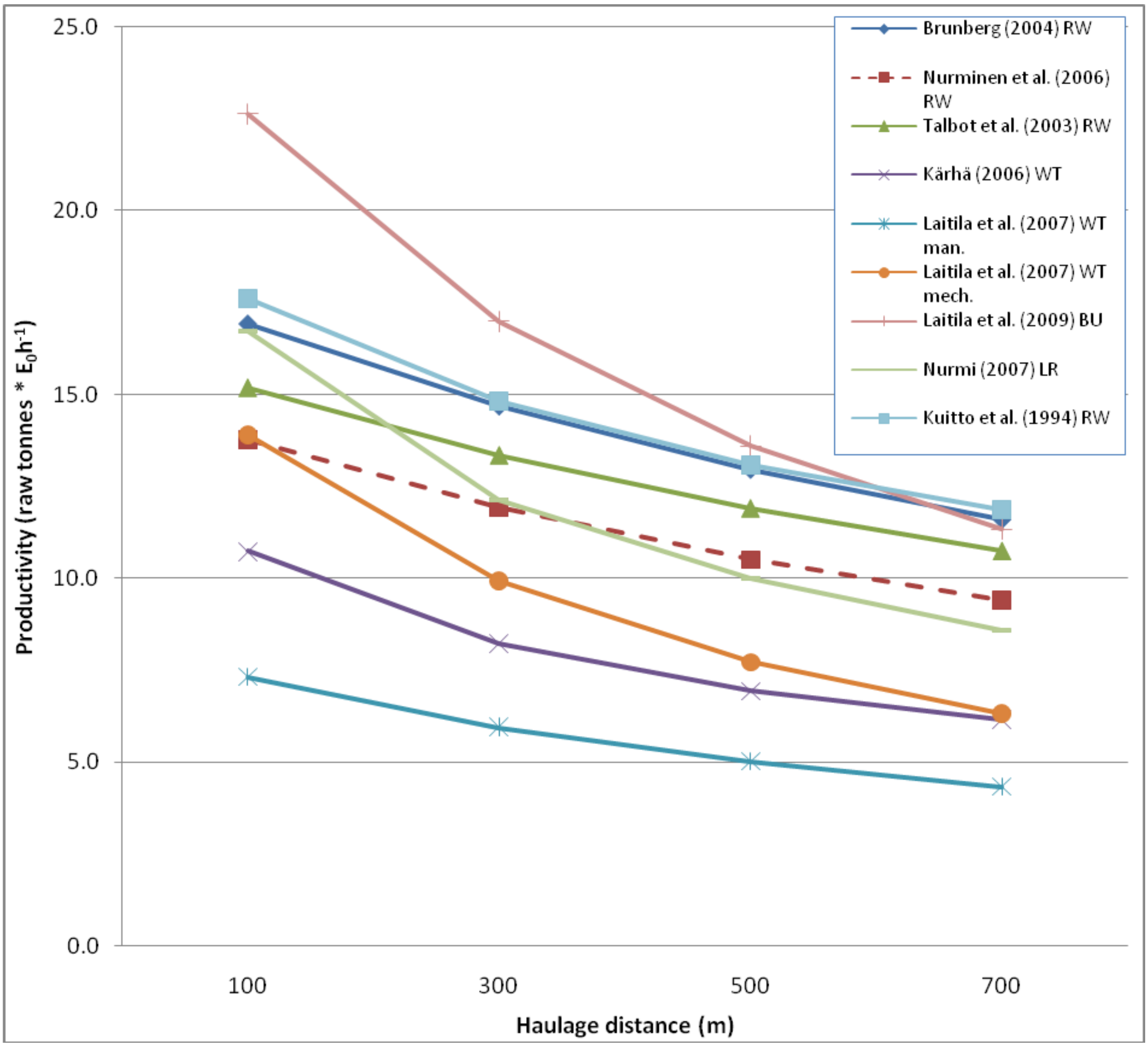

Figure 2. Synthesis of productivity estimates and results from time studies and simulations for forwarders transporting whole-trees (WT), logging residues (LR), bundles (BU) or roundwood (RW). Wherever the underlying models have allowed, the independent variables are the same in the different models. Otherwise, the parameter values and environmental configurations presented in each of the papers have been maintained. For a list of settings, assumptions and adaptions see Appendix II.

From the different studies included in Figure 2 it appears that forwarding of whole-trees (WT) generally has a lower productivity than forwarding of roundwood (RW). The main reasons for this are the low compaction of loose WT in the load space, as well as difficulties in handling the bulky and heterogeneous piles. Forwarding of logging residues (LR) after a final felling based on a special felling method (Nurmi, 2007) in fact has a higher productivity than forwarding whole-trees during thinnings in the studies presented here. Although LR has an even lower degree of compaction than WT, the larger piles, higher density along the strip roads and bigger loads due to a bigger machine and load space are the main reasons for the higher productivity in LR forwarding.

Forwarding of RW generally has the highest productivity (Figure 2) among the cut-to-length methods. The two functions produced by Brunberg (2004) and Kuitto *et al.* (1994) have similar results. Talbot *et al.* (2003) and Nurminen *et al.* (2006) both present a somewhat lower productivity. The highest productivity of all forwarding operations over shorter forwarding distances is obtained with the bundle (BU) forwarding function presented by Laitila (2009). This is probably the result of the large and uniform grapple volume obtained with the bundles and the presence of a sufficiently high proportion of solid volume to utilize fully the forwarders carrying capacity.

The more acute slope of the curves for WT, BU and LR extraction in Figure 2 is a result of the low proportion of solid volume in forest fuel assortments. This makes the forest fuel assortments more sensitive to forwarding distances, since the driving component makes up a higher proportion of the total work cycle than in roundwood haulage.

Gullberg's partially deductive time consumption model

Gullberg (1997a; 1997b) made an attempt to describe fully the time consumption of a forwarder, using independent variables and deductive parameters. After a thorough review of previous studies, four main work elements were identified and then fully described in terms of independent variables and coefficients. The entire model is reprinted from Gullberg (1997b) in Appendix III. Gullberg validated his model for the loading work element against an inductive model and presented the results graphically, showing good correspondence. He emphasized that rather than being the absolute truth, his model was intended to act as a framework or a starting point for further research, both deductive and inductive.

Gullberg's (1997b) approach is the most deductive model reviewed here; most of the models described in this paper are more empirically inductive (e.g. Brunberg, 2004). All sorts of hybrids between the two approaches are also possible. For example, Gullberg (2003b; 2003a) used existing time consumption functions for harvester work in thinning and final felling and modified these to mimic new machine systems and new silvicultural methods. Thinning of large trees was modeled through adding a penalty for obstacle trees to Brunberg's time consumption function for single-grip harvesters in final fellings (Brunberg, 1995), were no hindrance are considered. This approach can also be used on the deductive model in Appendix III, where parts of or entire work elements can be replaced with own models or Fig..

Discussion

Most of the data on time consumption in Nordic forestry is focused on roundwood extraction using the cut-to-length method, and knowledge in these areas is more than sufficient for use in long-term planning. The choice of function may affect the absolute level of productivity obtained in single-grip harvester and roundwood forwarding work, and this can be seen in Figure 1 and Figure 2. However, using the same function in all analyses at least ensures that any errors in productivity estimates are consistent between different scenarios.

Productivity functions for forest fuel extraction from young stands are, however, not as well developed as those for roundwood extraction (Table 1 and Table 2), and are also based on much smaller datasets. There are no generally applicable productivity functions covering environmental variations. Most existing functions also mainly consider systems under development, and are derived from comparative studies. New functions describing productivity for both harvesting and hauling whole-trees from young stands are therefore needed for use in long-term planning and for estimating potential harvest. Two promising approaches to creating such functions are simulations and theoretical/deductive functions.

I tested the usefulness and validity of Gullberg’s (1997b) framework for deductive functions. Five time studies relating to the forwarding of different assortments are compared with Gullberg’s model, which is adapted to the specific environments described in the studies. The method and context of each of the models are presented in Appendix III. Figure 3 and Figure 4 show the results of these comparisons and indicate that theoretical/deductive functions can be used to model forwarding of whole-trees in young stands with an acceptable level of precision.

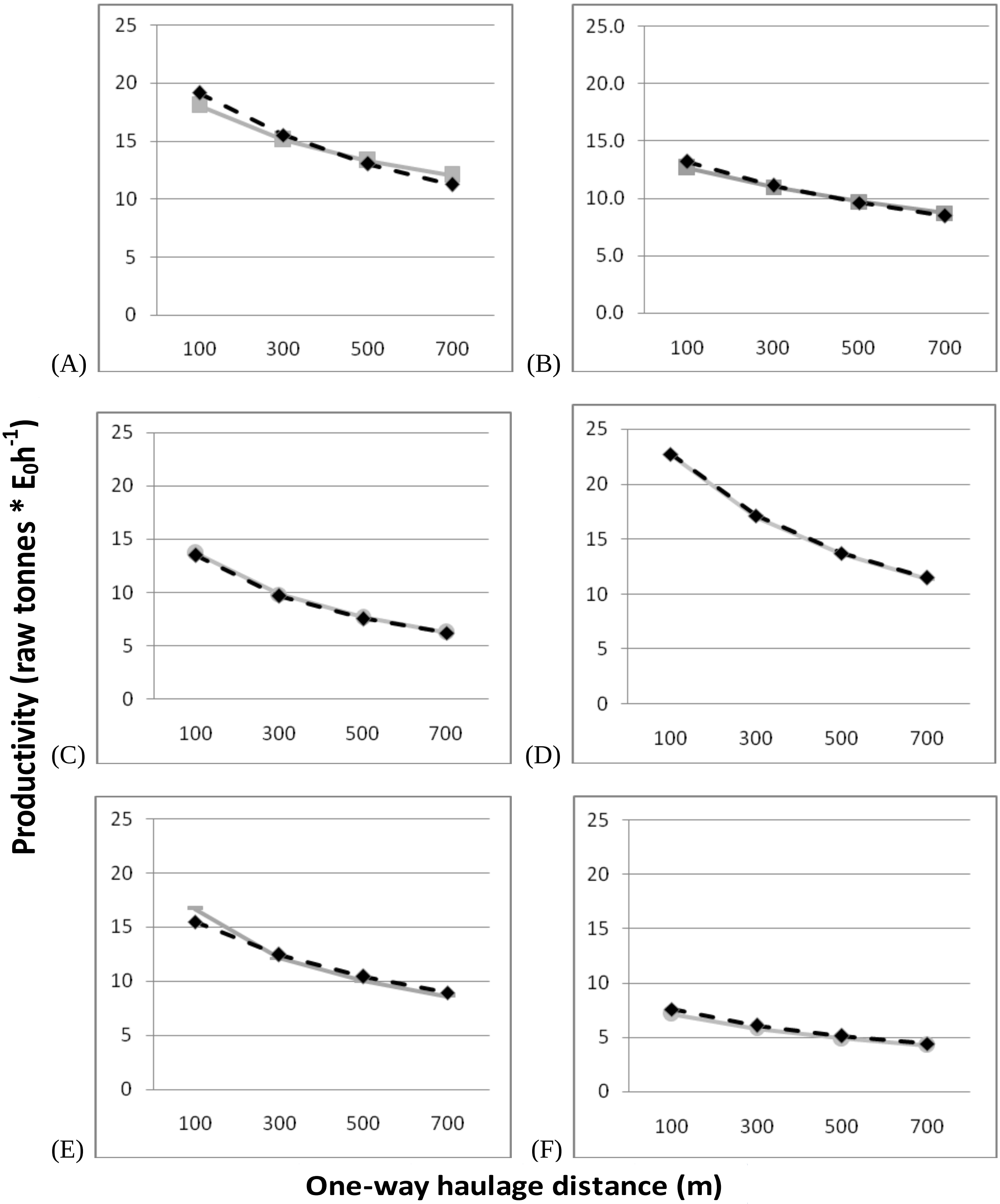

Figure 3. Modified versions of Gullberg's time consumption model for forest haulage (black dashed lines with diamonds) compared with Kuitto *et al.* (1994) (A), Nurminen *et al.* (2006) (B), Laitila *et al.* (2007) mechanized (C), Laitila *et al.* 2009 (D), Nurmi (2007) (E) and Laitila (2007) manual (F). For a detailed list of the assumptions and adaptions made to Gullberg's model, see Appendix III.

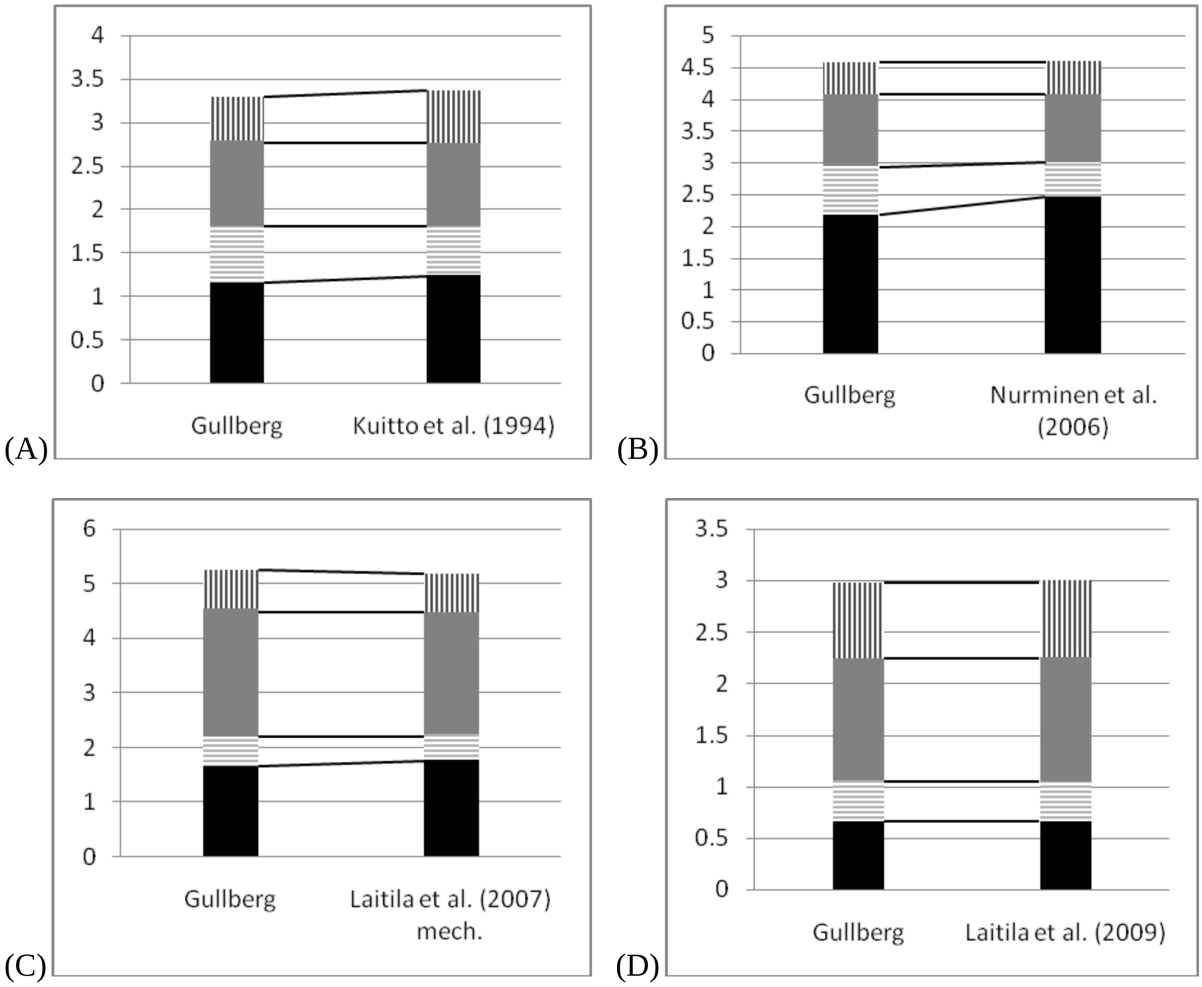

Figure 4. Time taken on the basis of four productivity functions in forest haulage and corresponding time taken on the basis of modified versions of Gullberg's model with a minimum of modifications made to the parameters and coefficients (see Appendix III). Transportation distances in all cases are 300 meters one-way. The different work elements are loading (black), driving while loading (horizontal bars), driving (grey) and unloading (vertical bars).

The overall time taken for handling different assortments with specific parameter settings is relatively easy to determine using Gullberg's model (Figure 3). Compared to Kuitto *et al.*'s (1994) model, the loading and unloading times predicted using Gullberg's model exhibit the largest deviations (Figure 3 and 4 (A)). Although this aspect of the time consumption models is the most developed and well described (Gullberg, 1997b; 1997a), it is also the most deductive and least supported by empirical facts. The good correspondence with Nurminen *et al.*'s (2006) model in Figure 3 and 4 (B) is only achieved when Nurminen *et al.*'s model is used to examine the forwarding of pulpwood. When forwarding sawlogs instead, the deviation is even bigger than that for the Kuitto *et al.* model (Fig. 3 and 4 (A))).

Gullberg's model corresponds particularly well to Laitila *et al.*'s (2007) model for whole-tree forwarding (Figure 3 and 4 (C)), and Laitila *et al.*'s (2009) model for bundle forwarding (Figure 3 and 4 (D)). It also appears in Fig. 4 (C), as in Figure 4 (A), that a difference in loading time is the single biggest deviation. The varying settings for the independent variables related to the loading work element presented in Appendix III also highlight the fact that loading is the most difficult work element to model.

Conclusions

Based on what is presented in this report, the following conclusions are made:

- When estimating forest fuel potential, most studies are based on existing cutting activity and forest fuel extraction is simply appended to the roundwood harvesting schedule.

- The accuracy of forest fuel extraction potential estimates and the goal fulfillment for the forest stakeholders would, assuming that forest fuel extraction affects forest management, be improved if it was fully incorporated into the standard logging potential estimate. To do so, however, is not an easy task; forest fuel is rarely extracted from young stands and thus neither the productivity, attitude and behavior of land owners nor the long-term effects on the forest and forest management are fully known. Thus, both optimization and simulation approaches in forest management analysis may have their disadvantages when considering forest fuel extraction.

- Harvester productivity is a complex subject, and is thus hard to model. Few and varying independent variables have been considered in the time studies examined. The simulation approach adopted by Eliasson (1999) has produced results that compare favorably to those from time studies. A simulation approach may be the best for modeling harvester productivity under conditions that are not yet known or fully investigated.

- Forwarder productivity, though still a complex subject, is perhaps somewhat simpler than harvester productivity to model.

- The deductive framework presented by Gullberg (1997b) seems to be flexible and appropriate when modeling forwarder productivity under new conditions.

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Appendix I

The general approach used when creating Figure 1 was to keep the independent variables constant between the functions. In most cases however, the functions did not allow environmental factors to be altered. The calculations underlying Figure 1 therefore seldom represent work performed under standard conditions.

In many cases, the dependent variables of the productivity functions were different than the one used on the y-axis in Figure 1 (cf. Table 1). If so, productivity expressed as number of trees has been derived from the average tree size for each productivity estimate. For example:

$$Productivity\ (N/h) = Productivity\ (m^3/h)\ /\ Avg.\ tree\ size\ (m^3)$$

For a list of functions, assumptions and adaptions, see Tab. 1.1 and 1.2.

Table 1.1. Functions, conversion factors and parameters upon which the curves in Fig. 1 were based (sub means solid under bark, sob means solid on bark and DM means dry matter).

Table 1.2. Studies from which the points in Fig. 1 were derived (thin. means thinning, acc. means accumulating, and PCT means pre-commercial thinning).

Study	Case, function	Assortment at strip road side
Nilsson 2009	Whole-tree thin., acc. felling head, selective harvest	Tree sections
Bergström et al. 2007	Whole-tree thin., acc. felling head, delayed PCT, five trees per cycle, fan-wise pattern	Whole-trees
Bergström et al. 2007	Whole-tree thin., acc. felling head, delayed PCT, corridor harvest, fan-wise pattern	Whole-trees
Bergström et al. 2007	Whole-tree thin., acc. felling head, first thin., five trees per cycle, fan-wise pattern	Whole-trees
Bergström et al. 2007	Whole-tree thin., acc. felling head, first thin., corridor harvest, fan-wise pattern	Whole-trees
Bergström et al. 2007	Whole-tree thin., acc. felling head, first thin., selective harvest	Whole-trees
Bergström 2009	Whole-tree thin., acc. felling head, first thin., selective harvest, >4cm	Whole-trees
Jylhä & Laitila 2007	Whole-tree thin., bundle harvester, mean over three stands	Bundles
Liss 2004	Whole-tree thin., acc. felling head, conv E_{15}/E_0 =1.333	Tree sections
Liss 1999	Whole-tree thin., acc. felling head, selective harvest	Whole-trees
Liss 1999	Whole-tree thin., acc. felling head, geometrical harvest	Whole-trees

Appendix II

The general approach used when creating Fig. 2 was to keep the independent variables constant between the functions. In most cases however, the functions did not allow the environmental factors to be altered. The calculations underlying Fig. 2 therefore seldom represent work performed under standard conditions.

In many cases, the dependent variables of the productivity functions in the studies were different from the one used on the y-axis in Fig. 2 (cf. Table 2). If so, productivity expressed in raw tonnes per E_0-hour was been calculated using the conversion factors in Tab. 2.1.

In many of the functions, a distinction is made between transportation distance while driving unloaded and loaded. In Fig. 2 however, the underlying transportation distance used in all cases was the same for both unloaded and loaded. Typically, 55-60% of the total driving distance is when the vehicle is not loaded. This is, however, taken into consideration in the pairwise comparisons of the functions in Fig. 3 and 4, and is explained in Appendix III.

Table 2.1. Functions, conversion factors and parameters upon which the curves in Fig. 2 were based.

				Conversion factors and parameter settings													
Study	Case, function	Abbreviation	Assortment at strip road side	E_{15}/E_0	raw ton / m^3 *	Extraction, m^3/ha	Driving speed loaded / unloaded, m/min	Driving speed when loading, m/min	Machine size	Load size, m^3	Surface structure	Slope	Tree size	Volume per work place (also grapple volume in loading), m^3	Grapple volume in unloading, m^3	Removal density, m^3 / 100 m	Strip road distance, m
Brunberg 2004	Thin.	Brunberg -04 TH	Pulpwood	1.08	0.95	60	56	-	Medium	12.9	1	1	0.1 m3	-	-	-	-
Kuitto et al. 1994	Thin.	Kuitto -94 TH	Pulpwood (long)	-	0.85	-	-	29	-	11.6	1	1	-	0.57	-	12	-
Nurminen et al. 2006	Thin., pine, overall model	Nurminen -06 TH	Pulpwood	-	0.85	60	-	27	-	11.6	-	-	-	-	-	-	20
Talbot et al. 2003	First thin., TWIN	Talbot -03 FTH	Roundwood	1.08	0.95	60	-	-	-	-	-	-	-	-	-	-	-
Kärhä 2006	Whole-tree thin., Figure 3	Kärhä -06 WT	Tree sections	-	0.866	(60)	-	-	-	6.2	-	-	-	-	-	(21)	-
Laitila et al. 2007	Mechanical felling	Laitila -07 mech. WT	Whole-trees	-	0.85	-	-	-	-	6.2	-	-	-	0.23	0.59	12	-
Laitila et al. 2007	Motormanual felling	Laitila -07 man. WT	Whole-trees	-	0.85	-	-	-	-	5.7	-	-	-	0.1	0.69	12	-
Laitila et al. 2009	Off-road transportation	Laitila -09 BU	Bundles	-	0.85	-	-	-	-	8.9	-	-	-	0.4	0.4	12	-
Nurmi 2007	M2 harvesting method	Nurmi -07 LR	Logging residues	-	-	-	-	-	-	8.1 **	-	-	-	-	-	-	-

* The unit m3 differs depending on which unit is used in the study

** Load size expressed in raw tonnes here

Appendix III

The general approach used when creating Fig. 3 and 4 was to adapt Gullberg's model as far as possible to the average conditions for each of the time studies considered in the pairwise comparisons. The relevant publications were, therefore, thoroughly examined for descriptions of the environmental factors. In some cases however, not all environmental factors of interest were mentioned. If so, values were assigned to the parameter either on the basis of similar studies or through guesswork. The calculations underlying Fig. 3 and 4 should, therefore, represent work performed in approximately the same environment.

Grapple area and pile size are two important variables for estimating the loading time consumption. As can be seen in Tab. 3.1, different approaches were used to assign values to these variables. This suggests that the loading time consumption model needs to be either investigated further or simplified.

Using the approach presented here to model forwarding work in an environment not yet studied will probably be beneficial, the alternative is to create a simulation model. However, when modeling an environment without a time study upon which to rely, faulty assumptions, for example about pile and grapple volume, may result in errors in estimates of time consumption.

For convenience, the full model presented by Gullberg (1997b) is reprinted with the kind permission of the author some pages ahead.

Table 3.1. Functions, conversion factors and parameters upon which the curves in Fig. 3 and 4 were based.

		Parameter in Gullbergs model																						
		Loading							Driving while loading					Driving[14]								Unloading		
Study, function	Machine type (study/Gullberg)	A	B	E	HV	VL	GA	FV	ST	VU	X	V100[12]	HL	A_{st}[11]	A_{ba}[11]	LA	Ykl	Lkl	H_{st}	H_{ba}	J	KC	GA	K
Kuitto et al. (1994)	Valmet 838/medium forw. thin	0.34	0.23	0.08	0.561	4.35	0.22	0.65	0.06	0.56	0.23	7	26.7	0.4	0.6	4.15	1	1	58[3]	52[3]	0.7	0.4	0.3	0.03
Nurminen et al. (2006)	Valmet 860/medium forw. thin	0.34	0.23	0.08	0.194	4.23	0.252	0.65	0.06	0.28	0.23	6.804	27[3]	0.4	0.6	4[5]	1	1	56[3]	44[3]	0.7	0.4	0.3	0.03
Laitila et al. (2007) mechanical	TJ810/small forw. thin	0.32	0.32	0.1	0.546	4.43	0.257	0.35	0.06	0.54	0.23	9.9	23.4	0.45	0.55	4[5]	1	1	47[3]	40[3]	0.7	0.4	0.389	0.05
Laitila et al. (2007) manual	TJ810/small forw. thin	0.32	0.32	0.1	0.356	4.43	0.0659	0.35	0.06	0.35	0.23	10.1	19.6	0.45	0.55	3.675	1	1	47[3]	40[3]	0.7	0.4	0.4459	0.05
Laitila et al. (2009)	TJ1010/medium forw. thin	0.218	0[8]	0.08	0.7966	2.69	0.3329	0.4649	0.06	0.796	0.23	12	25.1	0.4	0.6	7.45	1	1	66[10]	55[10]	0.7	0.2959	0.3329	0.03
Nurmi (2007)	Kockums 850/medium forw. clearcut	0.29	0.2	0.03	1.11	2[9]	0.29	0.659	0.06	1.11	0.3	10.92	28.7	0.4	0.6	7.335	1	1	60[3]	44[3]	0.7	0.4	0.313	0.03

[1] Pile volume set to volume per loading stop here due to lack of knowledge of average grapple volume

[2] Grapple area estimated by author after confering Gullberg's report and manufacturer figures

[3] Using driving speed for the work moment at hand presented in the study

[4] Pile volume set to average grapple volume in study here for better fit

[5] Load area derived from average load size presented in study at hand

[6] Pile volume set to volume per loading stop here for better fit

[7] Actual grapple area according to study at hand

[8] Based on the observation in the study at hand that loading time per bundle was constant, regardless of bundle size

[9] Derived to fit average grapple size observed in the study at hand

[10] Derived from the time consumption functions for driving in the study at hand

[11] Here used not as distance on strip road/main haul road, but as relationship driving loaded/driving unloaded, using general relationships found in studies at hand, with specific exceptions

[12] Using either average from study at hand or own assumptions

[13] Authors own assumption of increased GV during unloading

[14] Driving speed in all cases modeled using Brunberg's (2004) speed model

Lastning, min/m³f/Loading, min/m³ solid volume:

$$\left[\left(\frac{A+C\times AS}{2-e^{(-2\times HV/GV)}}+(D\times B\times VT)\times AF+\frac{A+B\times GV+C\times AS}{GV}\times HV\right)\times\left(1+E\times(VL-3)\right)\right]/\left(HV+AF\times VT\right.$$

Alternativ enklare modell utan hänsyn till svåra högar och flerhögslastning:
Alternative, simplified model without consideration to difficult piles and multiple pile loading:

$$\left[\left(\frac{A}{2-e^{(-2\times HV/GV)}}+\frac{A+B\times GV}{GV}\times HV\right)\times\left(1-E\times(VL-3)\right)\right]/HV$$

där

A, B, C, D, E = koefficienter i funktion över krancykeltid (se tabell)
coefficients in load cycle time function (see table)

HV = högvolym, m³f pb
pile volume, m³ solid ob

AS = andel svåra högar
proportion of difficult piles

AF = andel krancykler med flera högar = $\frac{\text{antal högar} - \text{antal krancykler}}{\text{antal krancykler}}$

proportion of multiple pile loading = $\frac{no.\ of\ piles - no.\ of\ loading\ cycles}{no.\ of\ loading\ cycles}$

VL = virkeslängd, m
log length

GV = maximal gripvolym, m³f pb = GA × VL × FV
maximum grapple volume, m³ solid volume ob = GA × VL × FV

GA = griparea, m²
grapple cross section, m²

FV = fastvolymandel
proportion solid wood

VT = volymtillskott vid flerhögshantering = HV om $HV \le \frac{GV}{2}$

$= \frac{GV}{2}$ om $HV > \frac{GV}{2}$

additional volume in multiple pile loading = HV *if* $HV \le \frac{GV}{2}$

$= \frac{GV}{2}$ *if* $HV > \frac{GV}{2}$

	GA	A		B		C	D	E	
Maskintyp *Machine type*		Gallr. *Thin.*	Slutavv. *Clear cut*	Gallr. *Thin.*	Slutavv. *Clear cut*			Gallr. *Thin.*	Slutavv. *Clear cut*
Traktor - liten *Tractor - small*	0,10	0,39	0,33	0,36	0,31	0,05	0,20	0,25	0,15
- mellan *- medium*	0,15	0,36	0,31	0,36	0,31	0,06	0,20	0,15	0,10
- stor *- large*	0,20	0,36	0,31	0,36	0,31	0,08	0,20	0,10	0,05
Skotare - liten *Forwarder - small*	0,20	0,32	0,27	0,32	0,27	0,08	0,20	0,10	0,05
- mellan *- medium*	0,30	0,34	0,29	0,23	0,20	0,09	0,20	0,08	0,03
- stor *- large*	0,40	0,36	0,31	0,17	0,15	0,10	0,20	0,05	0,02

	FV		
	Timmer *Saw logs*	2,5-5,5 m massaved *2.5-5.5 m pulpwood*	3 m massaved *3 m pulpwood*
Barr *Coniferous*	0,67	0,65	0,65
Löv *Decideous*	0,60	0,57	0,57

Körning under lastning, min/m³f/ Driving while loading, min/m³ solid:

$$\frac{ST}{VU}+\frac{KS}{HL}$$

ST = ställtid per flytt, min
fixed time per move, min

VU = volym per uppställningsplats = $X \times \sqrt{V100}$
volume per loading stop = $X \times \sqrt{V100}$

X = koefficient (0,23 för gallring och 0,30 för slutavverkning)
coefficient (0.23 for thinning and 0.30 for clear cutting)

V100 = volym per 100 m×m³ = $\frac{TU \times ASL \times SA}{AS \times 100}$

volume per 100 m, m³ solid = $\frac{TU \times ASL \times SA}{AS \times 100}$

KS = körsträcka per lastad m³f, m = $\frac{AS \times 10000}{ASL \times TU \times SA} = \frac{100}{V100}$

driving distance per m³ solid volume, m = $\frac{AS \times 10000}{ASL \times TU \times SA} = \frac{100}{V100}$

HL = körhastighet lastning, m/min = 9 + 8,5 × ln (KS × VU)
driving speed, m/min = 9 + 8.5 × ln (KS × VU)

TU = totaluttag, m³f/ha
yield m³ solid/ha

ASL = antal sortiment i lasset
no. of log sorts in load

AS = antal sortiment
no. of logs sorts

SA = stickvägsavstånd, m
strip-road spacing, m

Maskintyp/*Machine type*		**ST**
Vändbar stol *Swivel chair*	- körbar vänd bakåt *- possible to drive facing backwards*	0,06
	- ej körbar vänd bakåt *- not possible to drive facing backwards*	0,23
Ej vändbar stol/ *Non-swivel chair*		0,14

Körning, min/m³f/Driving, min/m³ solid volume:

$$\left(\frac{2A_{st}}{H_{st}}+\frac{2A_{ba}}{H_{ba}}+J\right)/(LA \times VL \times FV)$$

A_{st} = avstånd stickväg, m (enkel väg)
distance on strip road, m (one direction)

A_{ba} = avstånd basväg, m (enkel väg)
distance on main haul road, m (one direction)

LA = lastarea, m²
load cross section, m²

VL = virkeslängd, m
log length, m

FV = fastvolymandel
proportion solid volume

H_{st} = hastighet stickväg, m/min = H + I × (Ykl + Lkl)
driving speed on strip road, m/min = H + I × (Ykl + Lkl)

H_{ba} = hastighet basväg, m/min = F + G × (Ykl + Lkl)
driving speed on main haul road, m/min = F + G × (Ykl + Lkl)

Ykl = ytstrukturklass enligt terrängtypschema
surface obstacle class according to terrain classification scheme

Lkl = lutningsklass enligt terrängtypschema
slope class according terrain classification scheme

J = ställtider, min/lass
fixed times, min/load

		F	**G**	**H**	**I**	**J**	**LA**	
Maskintyp/*Machine type*							**3 m**	**- 5,5 m**
Traktor *Tractor*	- liten *- small*	130	-14	52	-4,7	0,7	1,6	1,6
	- mellan *- medium*	130	-14	52	-4,7	0,7	2,2	2,2
	- stor *- large*	130	-14	52	-4,7	0,7	2,7	2,7
Skotare *Forwarder*	- liten *- small*	120	-11	56	-4,7	0,7	3,5	2,7
	- mellan *- medium*	120	-11	60	-4,7	0,7	4,0	3,2
	- stor *- large*	120	-11	62	-4,7	0,7	6,0	5,0

Lossning, min/m³f/Unloading, min/m³ solid volume:

$$\frac{KC}{GA \times VL \times FV} \times (1 + K \times (L - 3))$$

KC = krancykeltid vid 3 m virkeslängd, min
loading cycle time for 3 m log length, min

GA = griparea, m²
grapple cross section, m²

VL = virkeslängd, m
log length, m

FV = fastvolymandel
proportion solid volume

K = koefficient för längdkorrigering
correction coefficient for log length

Uttrycket (1 + D × (L - 3)) kan lägst bli 1,0.
The expression (1 + D × (L - 3)) cannot be lower than 1.0

Maskintyp/*Machine type*		GA	KC	K
Traktor *Tractor*	- liten *- small*	0,10	0,40	0,15
	- mellan *- medium*	0,15	0,40	0,10
	- stor *- large*	0,20	0,40	0,05
Skotare *Forwarder*	- liten *- small*	0,20	0,40	0,05
	- mellan *- medium*	0,30	0,40	0,03
	- stor *- large*	0,40	0,40	0,02

FV	Timmer *Saw log*	2,5-5,5 m massaved *2.5-5.5 m pulpwood*	3 m massaved *3 m pulpwood*
Barr *Coniferous*	0,67	0,65	0,65
Löv *Decidious*	0,60	0,57	0,57

Korrektioner

De redovisade modellerna förutsätter att maskinerna klarar fulla lass och fulla gripar. Det kan därför vara nödvändigt att justera lassvolymerna vid svåra terrängförhållanden och stora snödjup. Detta gäller i synnerhet traktorekipage med odrivna griplastarvagnar.

Griparean i funktionsuttrycken för lastning och lossning kan sänkas enligt nedanstående formel om lyftkraften är otillräcklig.

$$\textit{Effektiv griparea} = \textit{griparea} \times \frac{\textit{nettolyftkraft vid}\ \frac{(\textit{kranräckvidd} - 4)}{2}}{\textit{griparea} \times \textit{virkeslängd} \times \textit{fastvolymandel} \times \textit{densitet} \times \textit{gravitation}}$$

Den effektiva griparean kan dock högst uppgå till tillgänglig griparea.