# Arbetsrapport

Från Skogforsk nr. 802–2013

# Analyses of forest management systems for increased harvest of small trees for energy purposes in Sweden

INFRES WP3 Task 3.2

Analys av skogsskötselsystem för ökat uttag av klenträd som bränslesortiment

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SKOGFORSK
SEVENTH FRAMEWORK PROGRAMME

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In the Arbetsrapporter series, Skogforsk presents results and conclusions from current projects. The reports contain background material, preliminary results, conclusions, and analyses from our research.

**Titel:**
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Analys av skogsskötselsystem för ökat uttag av klenträd som bränslesortiment.

**Bildtext:**
Partly delimbed energy wood at roadside.

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## Abstract

The objectives of the present study were to evaluate management systems where the forest stands are intentionally managed to create high stem density up to the first thinning stage to enable biomass harvest in early thinning, and to compare these systems with traditional management on the same sites.

The study was performed by simulating stand development for five different management scenarios and for three different site indices. Costs and revenues were calculated using cost functions and relevant data from operational forestry.

In the dense stand scenarios (4 000 stems /ha) the amounts harvested as forest fuel were 30–50% greater than those in the standard spacing scenarios (1 600–2 000 stems/ha). However, the dense young stands hampered future diameter increment and so reduced the amount of sawlogs and pulpwood produced in later thinnings and final felling.

The highest soil expectation values were found for the common practice scenarios with standard spacing, i.e. 1600–2000 stems/ha. Sensitivity analyses showed that, despite higher SEVs for the wide-spacing alternatives, the dense-stem scenarios have potential under certain circumstances and especially if logging costs for harvest of small trees can be reduced by at least 15% and/or with increased energy prices.

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# Preface

Finnish Forest Research Institute (Metla) is coordinating a research and development project 'Innovative and effective technology and logistics for forest residual biomass supply in the EU –INFRES'. The project is funded from the EU's 7th framework programme. INFRES aims at high efficiency and precise deliveries of woody feedstock to heat, power and biorefining industries.

INFRES concentrates to develop concrete machines for logging and processing of energy biomass together with transportation solutions and ICT systems to manage the entire supply chain. The aim is to improve the competitiveness of forest energy by reducing the fossil energy consumption and the material loss during the supply chains. New hybrid technology is demonstrated in machines and new improved cargo-space solutions are tested in chip trucks. Flexible fleet management systems are developed to run the harvesting, chipping and transport operations. In addition, the functionality and environmental effects of developed technologies are evaluated as a part of whole forest energy supply chain.

This publication is a part of the INFRES project. The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2012-2015] under grant agreement n°311881.

## Sammanfattning

Syftet med denna studie var att utvärdera skogsskötselsystem med hög stamtäthet i ungskogar av tall och jämföra med konventionellt förband efter röjning. Tanken med att skapa ungskogar med högre stamtäthet än normalt är att utnyttja den tidiga biomassaproduktionen till ett första uttag av klenträd som bränslesortiment, för att sedan övergå till ett konventionellt skötselprogam. Vi simulerade beståndsutvecklingar på tre olika ståndortsindex och fyra olika skötselscenarier. I jämförelsescenariot röjdes bestånden till standardförband 1 600–2 200 stammar/ha beroende på ståndortsindex. De tre scenarierna med tätt förband röjdes till 4 000 stammar/ha och sköttes med varierande tidpunkt för den första klenträdsgallringen med bränsleuttag. Intäkter från skogsbränsle, massaved och sågtimmer beräknades genom apteringssimulering kontrollerad av en aktuell prislista. Kostnad för drivning och skogsvård beräknades med data och kostnadsfunktioner från operativt skogsbruk. Beräkningar av markvärden och känslighetsanalyser av dessa gjordes för alla scenarier. I skötselscenarierna med täta ungskogar producerades 30–50 % mer biobränsle än i scenariot med konventionella förband. Däremot hämmade de täta förbanden diameterutvecklingen och reducerade volymen och värdet av rundvirkessortiment i kommande gallringar och slutavverkning. Den reducerade grundytan efter klenträdsgallringen minskade också den framtida volymtillväxten. De konventionella förbanden hade genomgående de högsta markvärdena. Känslighetsanalyser visar att det stamtäta scenariot där klenträdsgallringen skjuts till samma tidpunkt som en konventionell förstagallring har viss potential att utvecklas till ekonomiskt attraktivt. Om drivningskostnaden i klenträdsuttaget kan reduceras med ca 30 % så når vi samma markvärde som med konventionellt förband, men endast på de bördiga markerna. Högre priser på energisortiment och korta transportavstånd kan bidra till att göra täta förband ekonomiskt attraktiva.



## Summary

Well-managed forests play an important role in the switch to renewable energy systems with low impact on climate and environment. In Sweden, small trees are an interesting source of forest fuel. Studies show great potential and that there are 2.8 million hectares of young forest with trees shorter than 12 m and with biomass amounts exceeding 30 tons DM/ha. The objectives of the present study were to evaluate management systems where the forest stands are intentionally managed to create high stem density up to the first thinning stage to enable biomass harvest in early thinning, and to compare these systems with traditional management on the same sites.

The study was performed by simulating stand development for five different management scenarios and for three different site indices. Two common practice scenarios were simulated: regeneration by planting of genetically improved seedlings (P) and regeneration by direct seeding (1), both with standard spacing after pre-commercial thinning (1 600–2 200 stems/ha). All the scenarios were based on direct seeding and pre-commercial thinning to 4 000 stems/ha and an early harvest of small trees for forest fuel during thinning of the stand (2A, 2B, and 3). Stand development was followed to full rotation. Revenues from harvest of forest fuel, pulpwood and sawlogs were predicted through bucking

simulation of virtual stems controlled by a price list typically used in present harvesting operations. Costs of all operations were calculated using cost functions and relevant data from operational forestry. Economic analyses involved calculations of soil expectation values (SEVs) for the different scenarios and through sensitivity analyses varying interest rate, energy price and logging costs for small trees.

In the dense stand Scenarios (2A, 2B, and 3,) the amounts harvested as forest fuel were 30–50% greater than those in the common practice Scenarios (P and 1). However, the dense young stands hampered future diameter increment and so reduced the amount of sawlogs and pulpwood produced in later thinnings and final felling. Comparison between the scenarios showed considerable differences in frequencies of sawlogs in various diameter classes. P was predicted to produce more large sawlogs, followed by (1, 2A, 2B and 3). The effect of different site indices (SI) clearly indicated larger averages for T26 and decreasing averages at lower SI. Differences in predicted basic densities between SIs were moderate, increasing with decreasing SI, slightly lower for the P and 1 Scenarios when compared with (2A, 2B and 3).

The highest soil expectation values were found for the common practice scenarios with standard spacing, i.e. 1 600–2 000 stems/ha. In northern Sweden, the planting Scenario (P) was the best and in southern Sweden direct seeding (1) had the highest SEVs, mainly due to the need for larger and more expensive seedlings in the south.

Sensitivity analyses showed that, despite the higher SEVs for the wide-spacing alternatives, the dense-stem scenarios have potential, particularly Scenario (3), under certain circumstances and especially if logging costs for harvest of small trees can be reduced by at least 15% and/or with increased energy prices. The logging costs we used represent average costs using present equipment and machine operators. Even today, the best machine/operator combinations can reduce logging costs by up to 30% compared to the average. We believe there is great potential to reduce logging costs for small trees, both with improved machines and with proper training and selection of operators.

Product definitions and pricing for an unknown future market will always involve considerable uncertainties. For this reason, not only the economic but also the total volume and characterization figures may be considered.

The considerable effects on frequencies of different diameter classes of sawlogs from final fellings should be noted. Changes in flow of log sizes may lead to changes in future log pricing. To reach similar distributions of diameter classes from the alternative scenarios, rotation time may be prolonged or shortened. However, such changes will also change the economic value of the produced sawlogs and also affect the flow of pulp and fuelwood.

The effects of management on frequencies of stem faults and irregularities and effects on native wood characteristics might also affect the different scenarios. Such effects could not be evaluated in the scenario analyses but might be worth considering when decisions for alternative silviculture regimes are taken.

# Introduction

From a Swedish standpoint, sustainable, well-managed forests play an important role in the switch to renewable energy systems with a low impact on climate and environment. In 2012, biomass provided 34 per cent of the primary energy used in Sweden. The forest is the main contributor to this biomass, which comes from pulp and saw milling residues as well as primary forest fuels, i.e. fuels that comes directly from the forest. Primary forest fuels derive from four sources: unmerchantable wood, tops and branches from final felling, small trees from thinning, and stump wood. From an economic viewpoint, the first two sources are fully utilized in south and central Sweden, but long-distance transport of these products from northern Sweden are not yet efficient enough. Although they have the largest potential to supply biomass, stumps are only harvested at an experimental scale on a few 1 000 ha every year. However, small trees are an interesting source of forest fuel. Studies show that the potential is high and that there are 2.8 million hectares of young forest stands with trees heights less than 12 m and containing more than 30 tonnes DM/ha.

These dense stands have not been deliberately created through management; instead, it is a lack of silvicultural management that has produced these stands. Although private forest owners are aware of the benefits of pre-commercial thinning (PCT), their PCT activity is limited by time and the cost of hiring someone else to do the job. PCT (and cleaning) of young stands steadily decreased in the early 1990s, partly as an effect of the provisions of the 1994 Swedish Forestry Act, which removed the obligation to carry out cleaning PCT, and partly due to lack of forest workers. At the same time, the stem density in cleaned stands increased from approximately 2 000 to nearly 3 000 stems per ha, partly as an effect of denser stands prior to PCT perations.

The alternative to harvest biomass for energy in the first thinning of these dense young stands is often a costly pre-commercial thinning, followed by an ordinary thinning 3–5 years later, where roundwood products are extracted. In this comparison, energy harvest provides a better or as good economic result as conventional thinning when the harvested trees have an average stem volume of less than 0.05 $m^3$. However, while this provides the best financial return when treating a stand that already is too dense, it might not be the best economic management for a forest stand over a complete rotation age.

Preliminary economic analyses over a full rotation in a management system where the stands are deliberately managed for a high stem density up to first thinning to enable biomass harvest, have indicated an optimal stem density after PCT of around 3 600 stems/ha on intermediate sites in central Sweden.

# Objectives

The objectives of the present study were to evaluate management systems where the forest stands are intentionally managed to create high stem density up to the first thinning stage to enable biomass harvest in early thinning, and to compare these systems with traditional management on the same sites.

# Material and methods

## STANDS AND SITES

The analyses were performed at forest stand level. To capture differences in site characteristics, geography and climate, the consequence analyses were carried out at stand level and for three different site index (SI) classes for Scots pine (*Pinus sylvestris* L.). The site index classes (T18, T22 and T26) were chosen to be representative of the areal distribution of SI in Sweden, based on data from the Swedish National Forest Inventory.

For each SI class, a silvicultural management program was specified, representting the base-line (common practice) and three alternative silvicultural systems (scenarios) with denser stands until the time for the first round of wood thinning. For each of these four scenarios, values of a range of different indicators were calculated. All scenarios were based on young stands regenerated by direct seeding with more than 5 000 stems/ha before PCT, thereby promoting the growth of dense stands. As a comparison, a management program based on planting of genetically improved seedlings was analyzed. This represents the most commonly used regeneration method on Scots pine sites in Sweden today.

## SPECIFICATION OF ANALYZED SILVICULTURAL SCENARIOS

The idea behind the concept of an early biofuel harvest, before first thinning, is to make use of the extra growth achieved by leaving a larger number of stems after pre-commercial thinning. After the first biofuel harvest, the stands in all scenarios were treated according to current practice (i.e. base-line). This means that, in the early biofuel harvest at 10 m dominant height, the number of stems is reduced down to the level of the base-line stand. The early harvest involves the uptake of strip roads, resulting in somewhat denser stands between the strip roads after the first cutting, in comparison to the number of stems at the base-line scenario. In turn, this circumstance indicates that the need for the next thinning should not come later in these scenarios. However, despite this, we simulated two different scenarios here, of which one has a somewhat delayed ordinary first thinning. In the third scenario, with higher stem density, the biofuel harvest is not performed until ordinary time of first thinning (cf. base-line scenario).

In all scenarios and for all site index classes, the assumption is successful regeneration of Scots pine through directly-sown seedlings, which are cleaned at the seedling height of 1 m and pre-commercially thinned to the number of stems as shown below. A base-line scenario was also included in which genetically improved seedlings were planted.

**Analyzed scenarios:**

1. Base-line (common practice).
   – No. of stems after PCT: 1 600, 1 900 and 2 200 stems per ha at site index T18, T22 and T26 respectively. First thinning at a dominant tree height of 12–13 m.

2. A. Biofuel harvest at 10 m dom. Height.
   – No. of stems after PCT: 4000 stems per ha at all site index classes. First thinning at the same time as Base-line scenario.

2. B. Biofuel harvest at 10 m dom. Height.
   – No. of stems after PCT: 4 000 stems per ha at all site index classes. First thinning delayed five years compared to Base-line scenario.

3. Biofuel harvest performed at ordinary time of first thinning (cf. base-line scenario).
   – No. of stems after PCT: 4 000 stems per ha at all site index classes.

P. Planting with 2 000, 2 200 and 2 500 seedlings per ha at site index T18, T22 and T26 respectively. PCT to the same densities as Scenario (1).

## QUANTITATIVE ANALYSES

The growth of the young stands, i.e. up to 10 m dominant height, was calculated according to functions by Pettersson (1992) (Figure 1). According to these functions, the mean diameter, as well as the diameter of the thickest trees, is largely influenced by stem density. Calculated basal areas were also tested against available static basal area functions, with stem density and dominant height as independent variables.

After 10 m height, the development of all stands was calculated according to a stand growth simulator called SkogProd. This is a product developed in cooperation between Skogforsk and the Swedish University of Agricultural Sciences, and is based on single tree growth functions, according to Söderberg (1986). Appropriate thinning schedules were produced using the harvest planning tool INGVAR. At this stage, the amount of deciduous trees (*Betula sp.*) was set to 10% at site index T18 and T22 and 15% at site index T26.

All forest stand data (e.g. stem density, basal area, diameter, volume) at chosen points of time for thinning and final cutting was obtained from the growth simulator. Built-in functions for diameter and height distributions produced data for individual trees, which in turn was used in the bucking functions and final assessment of the different products.

All thinnings were performed as thinning from below (low thinnings), with a strip road distance of 22 m and strip road width of 4 m. The final stand age was the same for all scenarios within each site index class. The rotation ages for site indices T18, T22 and T26 were set to 103, 93 and 80 years, respectively.

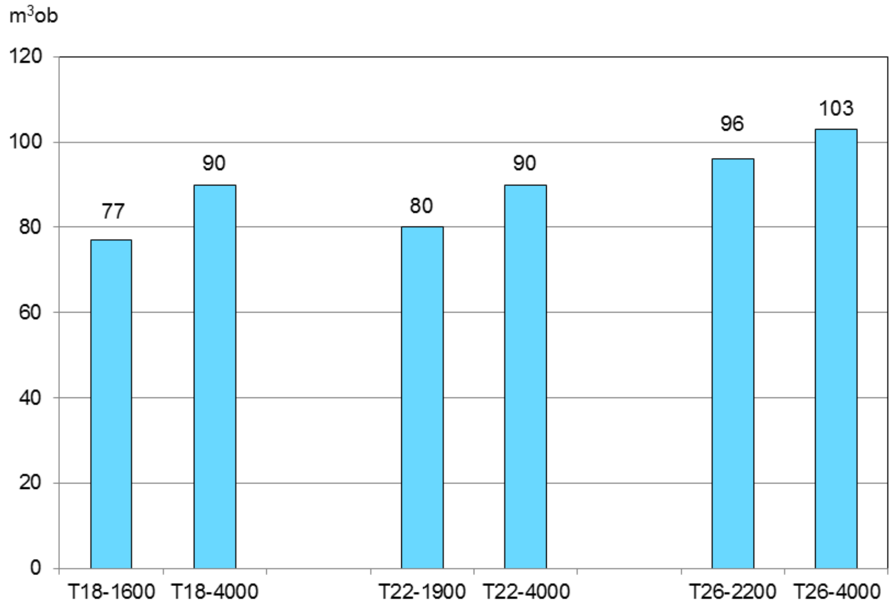


Figure 1.
Stem volume at the different stem densities and site indices at a dominant tree height of 10 m (according to functions by Pettersson, 1992).

The understory was not cleaned to reduce undersized trees, in neither early biofuel harvesting nor conventional first thinning operations. It was assumed that most of the small stems (<5 cm diameter) would be removed at harvesting and the rest to be drained before next harvest.

The minimum diameter for harvesting pulp wood trees was set to 8 cm at breast height and for harvesting biofuel 5 cm at breast height. The minimum top diameter for pulp-wood was set to 5 cm.

## HARVESTING OF BIOFUEL

The processing of the trees in the biofuel harvest was assumed to be performed according to the so called ”coarse delimbing”, leaving the major part (75%) of the biomass from the branches and all needles at the site.

At harvest, individual tree data (diameter and height) was generated. Trees, or parts of trees were thinned, depending on a given thinning grade, thinning form and area of the strip roads. All trees were removed in the strip road (thinning quotient 1.0). When harvesting biofuel, a special algorithm was used, selecting first the trees in the strip road and then trees (low thinning, min. diameter 5 cm) until the required number of main stems remained. The harvested biomass of these trees was calculated using functions presented by Repola (2008; 2009).

In these calculations, future tree growth was not reduced on account of the extra removal of nutrients at biofuel thinnings.

## ESTIMATIONS OF LABOR REQUIREMENTS AND HARVESTING COSTS

Productivities and cost of works that are independent of stand factors or amount of work per ha have been taken from the studies of productivity and costs in Swedish forestry (Brunberg, 2010; 2012a; 2012b) and the correspon-ding study of costs in forest fuel operations (Brunberg, 2012c). Productivities and costs dependent on stand factors and amount of work per ha has been calculated using functions from productivity norms or using updated functions intended for internal use at Skogforsk. The areas of the assumed final felling stands were set at 2.6 ha for southern Sweden (Kronoberg county) and 5.7 ha in northern Sweden (Västerbotten county), i.e. the average area for final fellings in these two counties according to the Swedish Forest Agency (Skogsstatistisk årsbok, 2012). It was assumed that two thinning stands close to one other and of the same size as the final felling stands can be thinned at the same time, i.e. fixed costs for a thinning is divided over twice the area as the fixed costs for a final felling.

Work times for personnel working with silviculture, planting, pre-commercial thinning etc. are presented as work hours per ha. The work time for machine work is presented as gross effective hours ($G_{15}$-hours) per ha, and must be divided by the degree of machine utilization to obtain the total work time per ha. For both kinds of work, it has been assumed that not all of the possible work time is used for the intended work task, as some time is used for voca-tional training, meetings, etc. Consequently, it was assumed that 210 of the theoretically possible 223 work days could be used for the work task, and the calculated work times were multiplied by 223/210 to compensate for that.

### Silvicultural work

In this report silvicultural costs are defined as the costs for establishment and management of the young stand until commercial harvest can begin.

#### Stand establishment

Stand establishment costs are divided into three parts: cleaning of old unviable undergrowth, soil preparation by scarification, and planting or seeding of the new trees.

The costs of cleaning old undergrowth are set at an average cost per ha, i.e. 1 150 SEK/ha for southern Sweden and 1 010 SEK/ha for northern Sweden, based on Brunberg (2012c). Scarification costs are also set as averages for southern (2 070 SEK/ha) and northern (1 780 SEK/ha) Sweden (Brunberg, 2012c).

In the base-line scenario, the forest stands are replanted using containerized seedlings after scarification. In all other scenarios, the forests managed for dense young stands are regenerated with integrated scarification and mechanical seeding.

In northern Sweden, the costs for seedlings were 1.05 SEK/seedling and the cost for planting was 1.0 SEK per seedling. In southern Sweden replanting costs are higher with a price per seedling of 2.65 SEK and a cost for planting of 1.50 SEK per seedling. The planting costs refer to planting work in normal conditions and an hourly cost of the planter at 220 SEK per hour. In 2011, the costs for integrated scarification and seeding were 4 470 SEK per ha in southern Sweden and 3 700 SEK per ha in northern Sweden according to (Brunberg, 2012).

### Management of young stands

The base-line scenario consisted of two PCTs of the stand, one early PCT to reduce competition from naturally regenerating deciduous trees and one at approximately 4 m stand height to space the trees to form an acceptable stand density. On the lowest site index, T18, i.e. least fertile stands, no early PCT took place but only the later spacing. When the forests were managed for dense young stands, the PCT made at 3–4 m stand height was aimed at producing denser, still evenly-spaced stands than in the base-line scenario.

The work time in PCT has been calculated using the performance standard of Bergstrand et al. (1986), reduced by 10 per cent based on the findings of Ligné (2004). The hourly costs of forest workers working with PCT are 280 SEK per hour and, in addition to the direct work cost, there is a fixed starting cost per stand of 1 500 SEK.

## Commercial harvesting operations

In the studied silvicultural management scenarios, three kinds of harvesting operations took place: forest fuel thinning, roundwood thinning and final felling. Forest fuel thinning only took place in the scenarios where the forest was managed for dense young stands. In Table 1, extraction distances for the thinning operations and final felling operations in the different parts of Sweden are presented. In Table 2, machine costs per gross effective hour are presented for the three kinds of harvesting operations. As the same base machines are assumed to be used in the forest fuel thinning and round wood thinning, these costs are identical. Relocation of machines between stands was calculated as the cost for 3 lost machine hours and the use of a low-bed trailer for 2 hours at a cost of 1 100 SEK per hour for each relocated machine.

Table 1.
Extraction distances in thinning and final felling 2011 according to Brunberg (2012).

| | Thinning | Final felling |
|---|---|---|
| Southern Sweden | 372 m | 361 m |
| Northern Sweden | 484 m | 478 m |

Table 2.
Machine costs (SEK per gross effective hour ($G_{15}$)) in harvesting operations.

| | Harvester cost | Forwarder cost |
|---|---|---|
| Forest fuel thinning | 1023 | 819 |
| Round wood thinning | 1023 | 819 |
| Final felling | 1139 | 899 |
| Residue extraction | | 819 |

Forest fuel thinnings were carried out to extract only one product, biomass as partly delimbed tree sections. The harvester and forwarder work time was calculated according to (Brunberg, 2011).

Time consumption for harvesters and forwarders in roundwood thinning and final felling were calculated using functions intended for internal use at Skogforsk (Brunberg, 2012 pers. comm.). In all final felling operations, logging residues were extracted for use as a forest fuel, as this is routine practice in current final felling operations.

## ROUNDWOOD PRODUCTS – PREDICTED VALUES AND CHARACTERISTICS

Comparative valuations and log characteristics from final fellings were predictted by bucking simulations of all individual stems from each of the different forest management scenarios presented above. Values of thinning operations were predicted by simple assumptions and wood values according to Table 3. Valuations of logs from thinning operations were carried out using predicted DBH (tree diameter at breast height, 1.3 m) and total height averages per scenario and thinning operation.  From these averages, stem size distributions were generated, providing a maximum volume of sawlog dimensions (small and ordinary diameter) multiplied by standardized proportion constants, reflecting common degrees of downgrading from sawlogs to pulpwood.

Table 3.
Principles of bucking regimes (sawlogs and pulpwood) for predicting log values.

| Logging operation | Proportion of sawlogs | Sawlog price |
|---|---|---|
| 1st thinning | 100% pulpwood | |
| 2nd thinning | 60% of maximum sawlog volume[1)] | 375 SEK/$m^3$sub |
| 3rd thinning | 75% of maximum sawlog volume[1)] | 400 SEK/$m^3$sub |
| Final felling | Bucking analyses based on pricing of log diameter and length | Ref. to pricelist (Appendix 1) |

[1)] Values of logs from thinning operations were calculated as follows: Small diameter pine sawlogs 14–17 cm top diameter (ub), 375 SEK/$m^3$sub. Pine sawlogs ≥18 cm top diameter (ub), 450 SEK/$m^3$sub. 2nd thinnings generated small diameter sawlogs only. 3rd thinnings were assumed to generate 2/3 small diameter sawlogs and 1/3 ordinary sawlogs of top diameters ≥18 cm. Pulpwood prices were set to 275 SEK/$m^3$sub of pine and 270 SEK/$m^3$sub of birch respectively.

### Bucking conditions at simulated final felling

Virtual individual stem profiles were produced from all final felling trees by combining individual tree DBH and height from the growth simulator described above and taper functions (Edgren & Nylinder, 1949). Bucking simulations were performed by the optimization software “Skogforsk TimAn 3.0”, where bucking of each individual virtual stem profile was controlled by a standard pricelist and apportionment matrices according to requested combinations of log diameters and lengths (Appendix 1). The apportionment requirements were satisfied as long as the maximum value of a log, according to the pricelist, was not reduced by more than 1%. To make the results from the bucking simulations realistic, statistically-based (from harvester production files) frequencies of stem faults and irregularities and their longitudinal distributions were added to the virtual stem profiles before running the simulations. Lack of existing statistically evident results in terms of possible differences in frequencies of stem faults and irregularities between geographic regions, site fertility classes or simulated management regimes justified a similar basis for induced fault frequencies in all simulation scenarios.

The percentages of different quality classes applied on the bucking simulations were based on VMF statistics from central Sweden (based on VMR 1–07) given in Appendix 1, Table A1.3.

Valuation of wood quality characteristics, such as strength, durability, visual properties, dry substance, and processability of fibers, is complex and highly dependent on the type of products and manufacturing processes to be used along different value chains. Quality index from stem pricing (Möller et al., 2005) is a simple and objective way to adjust value from differences in wood characteristics from statistically shown effects predicted by tree age in relation to DBH. This was applied by using the quality index implemented by Södra, Figure 2.

| Tall | Grundytevägd brösthöjdsdiameter i cm på bark | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12 | 14 | 16 | 18 | 20 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 |
| Totalålder | | | | | | | | | | | | | |
| 135+ | | | | | | | | 106 | 106 | 104 | 104 | 102 | 102 |
| 125-135 | | | | | | | 106 | 106 | 104 | 104 | 102 | 102 | 100 |
| 115-125 | | | | | | 106 | 106 | 106 | 104 | 104 | 102 | 100 | 100 |
| 105-115 | | | | | 106 | 106 | 106 | 104 | 104 | 102 | 102 | 100 | 100 |
| 95-105 | | | | 106 | 106 | 106 | 104 | 104 | 102 | 102 | 100 | 100 | 100 |
| 85-95 | | | 106 | 106 | 106 | 104 | 104 | 102 | 102 | 100 | 100 | 100 | 98 |
| 75-85 | | 106 | 106 | 106 | 104 | 104 | 102 | 102 | 100 | 100 | 98 | 98 | 96 |
| 65-75 | 102 | 104 | 104 | 104 | 104 | 102 | 102 | 100 | 100 | 98 | 96 | 96 | 94 |
| 57-65 | 102 | 102 | 102 | 102 | 102 | 100 | 98 | 98 | 96 | 94 | 94 | 94 | 94 |
| 53-57 | 102 | 102 | 102 | 102 | 100 | 100 | 98 | 96 | 96 | 94 | 94 | 94 | |
| 48-52 | 102 | 102 | 102 | 100 | 100 | 98 | 96 | 96 | 94 | 94 | | | |
| 43-47 | 100 | 100 | 100 | 100 | 98 | 96 | 94 | 94 | 94 | | | | |
| 38-42 | 100 | 100 | 100 | 98 | 96 | 94 | 94 | | | | | | |
| 33-37 | 100 | 100 | 98 | 96 | 94 | | | | | | | | |
| 28-32 | 100 | 98 | 96 | 94 | | | | | | | | | |
| 23-27 | 98 | 96 | 94 | | | | | | | | | | |
| -22 | 96 | 94 | | | | | | | | | | | |

Figure 2.
Quality index (%) for stem pricing according to a stem pricelist implemented by Södra (2012). Indicated index values (%) were multiplied with original prices from the bucking simulations described above and in appendix xx. [Adjusted price = (Index/100) × base price]. NB: "Tall" = pine "Totalålder"= Total age. "Grundytevägd brösthöjdsdiameter i cm på bark "= Basal area weighted DBH (o.b) in cm.

The valuation of log products from bucking simulations of final fellings and the simpler evaluation method used for thinnings resulted in predicted revenues (SEK) from each scenario. Different ways to express economic values have been applied. One way to make comparisons was to calculate discounted revenues (present net revenues) at 2.5 % interest rate. Another simple but easy to understand comparison was made by taking the sum of nominal revenues divided by rotation age.

In addition to predicted distributions of sawlog diameter and lengths, an attempt was made to predict differences in internal wood properties of individual logs. Basic density and heartwood proportion were predicted by models according to Wilhelmsson et al. (2002), while branch thickness and sound knots were predicted by models according to Moberg (2006) and Moberg et al., 2006 respectively. Furthermore, fiber properties were predicted from models developed by (Ekenstedt et al. 2003) and bark thicknesses were predicted according to Hannrup. Most of the functions for predicting internal wood properties require the number of annual rings of log cross-sections or mean annual ring widths. To enable this, additional functions (Wilhelmsson, 2006) for predicting numbers of annual rings in cross-sections were used.

## ECONOMIC ANALYSES

Combining the calculated costs and revenues, we have calculated the soil expectation value (SEV) of the different management scenarios and on different site types. The default interest rate was set to 2.5%, a value commonly used in analyses used for decision support in Swedish operational forestry (Sonesson et al., 2011; Simonsen et al., 2008). Sensitivity analyses with varying interest rates, energy prices and logging costs for extraction of small trees in first thinning were carried out. The price at the energy plant for energy from forest biomass was set to 202 SEK/MWh.

# Results

## HARVESTED WOOD QUANTITIES

Total harvested amounts of solid volume ($m^3$sub) and biomass (d.w.) from thinnings and final cutting in the analyzed scenarios are presented in Table 4. On the less fertile site types (T18 and T22), the base-line scenario gave the best total harvested yields, both in terms of solid stem volume and extracted biomass. On the more fertile site type (T26), the total amount of harvested biomass in Scenario (3) was on the same level, or slightly higher, than that of the base-line. However, the base-line scenario for harvested amounts of solid stem volume was superior also at this site type. When the base-line scenario with planting of genetically improved seedlings is also included, the total amount of harvested solid stem volume was even more improved (Figure 3–4).

The amounts of forest fuel extracted from the different scenarios are presented in Figure 5. Not surprisingly, the scenarios with forest fuel thinning consistently showed the highest total amounts. The greatest amounts were at all site types found in Scenario (3), with delayed forest fuel thinning. However, the amounts of harvested forest residues at final felling were consistently highest in the base-line scenarios.

Despite the additional forest fuel thinning operation, the highest amounts of nutrient removals were found in the base-line scenarios, which was due to the higher tree volume stock at final felling. Moreover, the nutrient removals in the forest fuel thinnings were somewhat limited due to the harvesting technique (coarse delimbing), removing only 25% of the branches and leaving all needles at the site.

Table 4.
Harvested amounts of biomass (d.w.) and/or solid volume (m$^3$fub) from thinnings and final cutting in the analyzed scenarios.

| T18-1-Base 1 600 stems ha$^{-1}$ | | | | T22-1-Base 1 900 stems ha$^{-1}$ | | | | T26-1-Base 2 200 stems ha$^{-1}$ | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) |
| 58 | 17.2 | 37 | 13.4 | 43 | 18.1 | 37 | 12.9 | 30 | 20.6 | 40 | 12.6 |
| | | | | 63 | 22.5 | 42 | 17.2 | 45 | 29.9 | 50 | 18.1 |
| 103 | 115.5 | 201 | 23.5 | 93 | 118.8 | 206 | 27.3 | 80 | 185.9 | 334 | 30.5 |
| **Sum** | **132.7** | **238** | | **Sum** | **159.4** | **285** | | **Sum** | **236.4** | **424** | |
| T18-2A 4 000 stems ha$^{-1}$ | | | | T22-2A 4 000 stems ha$^{-1}$ | | | | T26-2A 4 000 stems ha$^{-1}$ | | | |
| Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) |
| 43 | 9.7 | | 8.6 | 33 | 9.9 | | 8.5 | 25 | 10.6 | | 8.8 |
| 58 | 11.4 | 20 | 11.4 | 43 | 12.1 | 22 | 11.3 | 30 | 11.6 | 19 | 11.4 |
| | | | | 63 | 17.0 | 31 | 16.4 | 45 | 24.0 | 38 | 18.2 |
| 103 | 101.4 | 176 | 22.1 | 93 | 111.9 | 196 | 25.7 | 80 | 181.6 | 328 | 29.5 |
| **Sum** | **122.5** | **196** | | **Sum** | **150.9** | **249** | | **Sum** | **227.8** | **385** | |
| T18-2B 4 000 stems ha$^{-1}$ | | | | T22-2B 4 000 stems ha$^{-1}$ | | | | T26-2B 4 000 stems ha$^{-1}$ | | | |
| Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) |
| 43 | 9.7 | | 8.6 | 33 | 9.9 | | | 25 | 10.6 | | 8.8 |
| 63 | 13.4 | 23 | 11.8 | 48 | 14.8 | 28 | 12.1 | 35 | 17.0 | 27 | 12.8 |
| | | | | 68 | 18.7 | 34 | 17.0 | 50 | 27.2 | 43 | 18.9 |
| 103 | 98.7 | 172 | 21.9 | 93 | 107.5 | 188 | 25.5 | 80 | 177.2 | 319 | 28.8 |
| **Sum** | **121.8** | **195** | | **Sum** | **150.9** | **250** | | **Sum** | **232.0** | **389** | |
| T18-3 4 000 stems ha$^{-1}$ | | | | T22-3 4 000 stems ha$^{-1}$ | | | | T26-3 4 000 stems ha$^{-1}$ | | | |
| Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) | Stand age | ton d.w. | m$^3$fub | diam. (dgv, cm) |
| 58 | 18.6 | | 10.0 | 43 | 23.2 | | 9.9 | 30 | 20.7 | | 10.3 |
| 83 | 15.1 | 26 | 13.4 | 58 | 14.7 | 26 | 13.0 | 40 | 21.3 | 33 | 14.1 |
| | | | | 78 | 20.4 | 36 | 17.8 | 55 | 29.2 | 47 | 19.9 |
| 103 | 85.5 | 147 | 20.7 | 93 | 99.3 | 172 | 24.5 | 80 | 168.9 | 305 | 28.1 |
| **Sum** | **119.2** | **173** | | **Sum** | **157.6** | **234** | | **Sum** | **240.1** | **385** | |

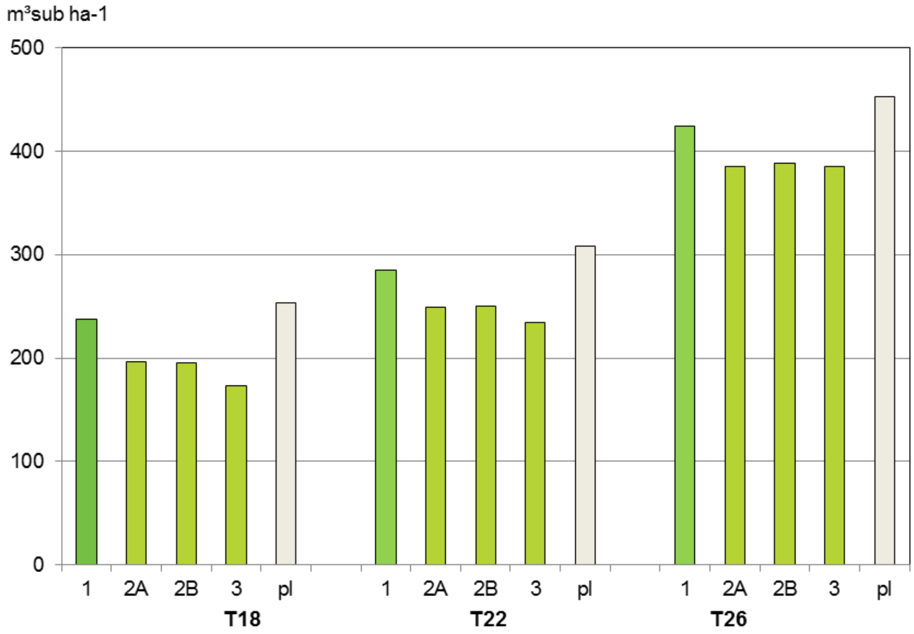


Figure 3.
Harvested total amounts solid volume (m³fub) from thinnings and final cutting in the analyzed scenarios.

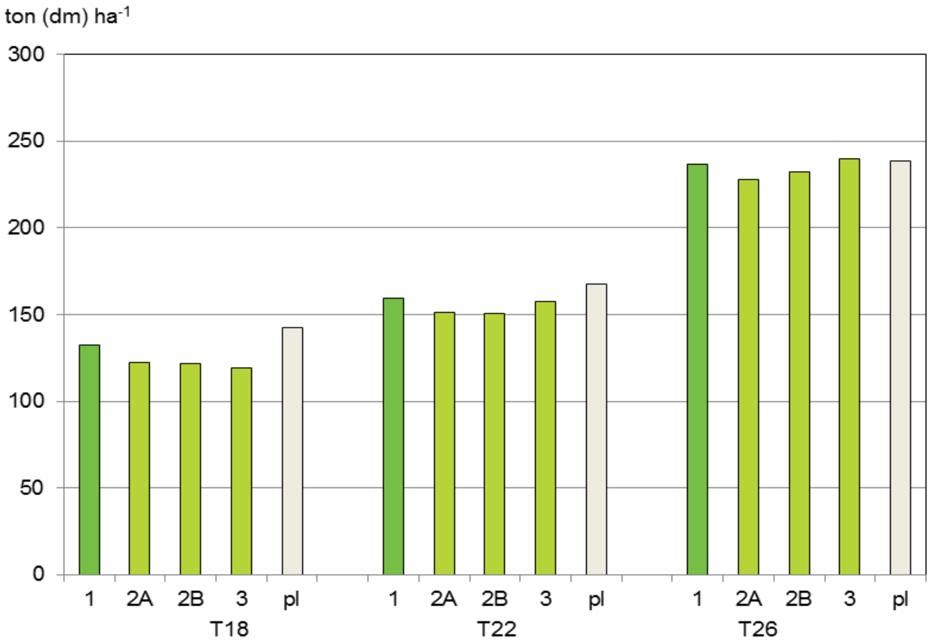


Figure 4.
Harvested amounts of biomass (d.w.) from thinnings and final cutting in the analyzed scenarios.

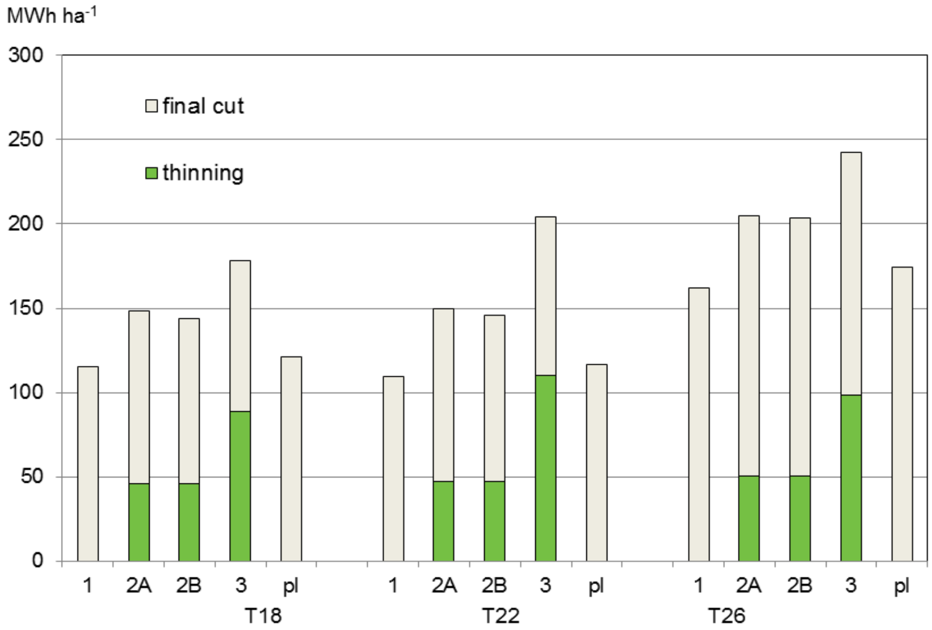


Figure 4.
Amounts of forest fuel extracted in the different scenarios.

## VALUATION AND CHARACTERIZATION OF WOOD PRODUCTION

Revenues from the different scenarios are presented as nominal revenues per product and hectare divided by rotation age (Figure 6) and present net revenues (Figure 7). Scenario P (= planting) generated the highest predicted revenues followed by the base Scenario (1). The steep increase in revenues as site index increased was also evident. Differences in frequencies of sawlogs into diameter classes were considerable, when comparing the scenarios. P was predicted to produce more larger sawlogs followed by 1, 2A, 2B and 3. The effect of different SI clearly indicated larger averages for T26 and decreasing trends with lower SI. Differences in predicted basic densities were moderate in the different SIs, increasing with decreasing SI, slightly lower for the 1 scenarios P and 1 when compared with 2A, 2B and 3. (Figure 11–13). As similar diameter growth/year was a prerequisite for the similar scenarios in northern (latitude 64°, altitude 200 m) and southern (latitude 57°, altitude 165 m) Sweden, differences in length of the growing seasons affect the predicted basic density. A difference of + 27 kg/$m^3$sub in arithmetic average was predicted for the southern alternative compared with the northern one. The relationship was similar regardless of the products (Figure 14). However, a comparison of predicted thickest branches goes in favor of the products from the northern growth conditions.

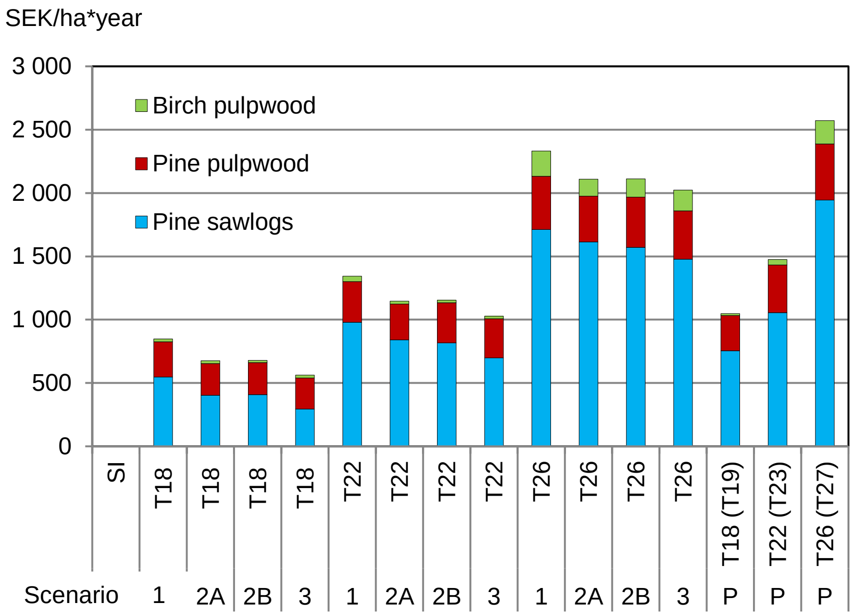


Figure 6.
Nominal revenues per hectare and year by scenario (SEK) (final felling and thinning), by sawlog and pulpwood products and site indices (SI). (0% interest rate).

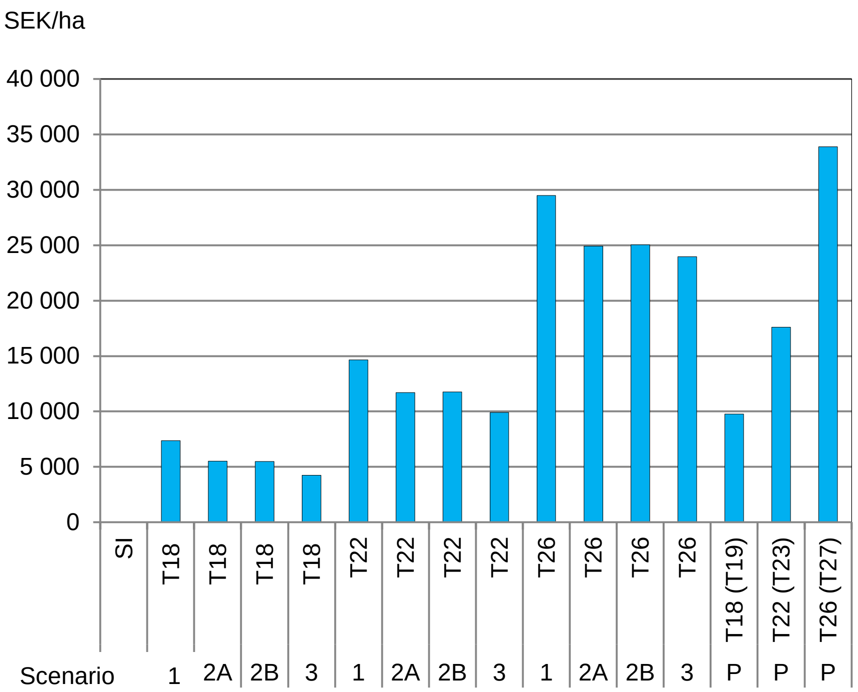


Figure 7.
Present net revenues (SEK) of all log products per ha and scenario at 2.5 % interest rate.

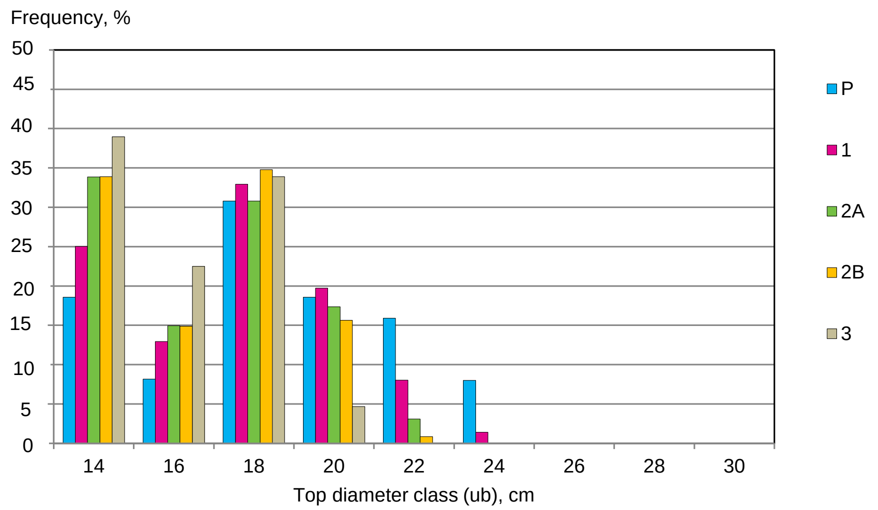


Figure 8.
Predicted diameter distributions of sawlogs from final felling on a T18 site by scenario.

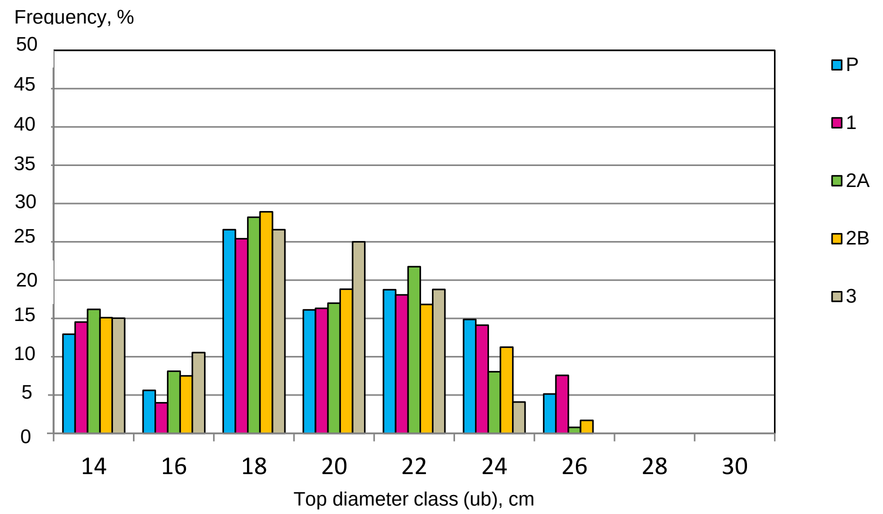


Figure 9.
Predicted diameter distributions of sawlogs from final felling on a T22 site by scenario.

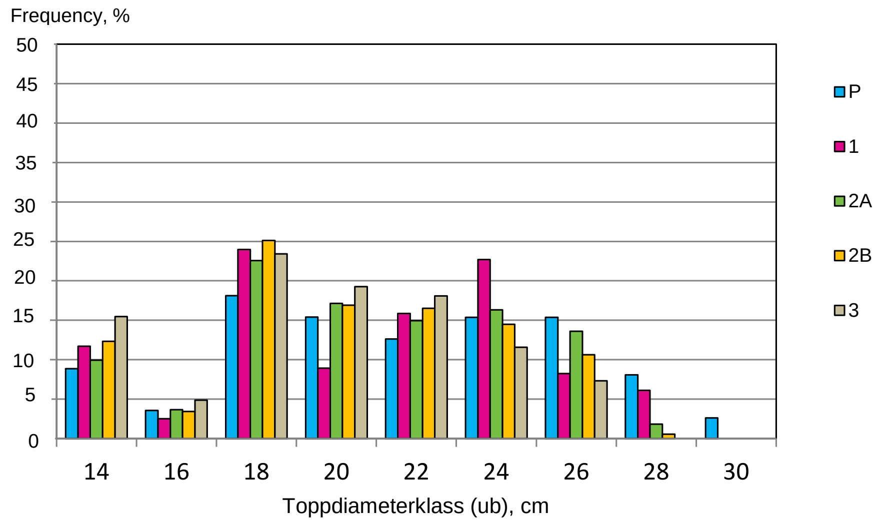


Figure 10.
Predicted diameter distributions of sawlogs from final felling on a T26 site by scenario.

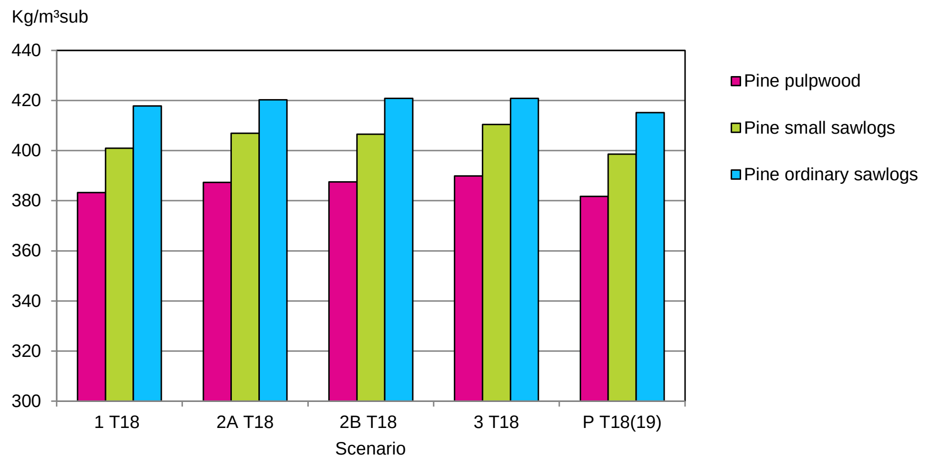


Figure 11.
Predicted basic density by product and scenario. Logs from simulated final felling on a T18 site at latitude 64° and altitude 200 m.

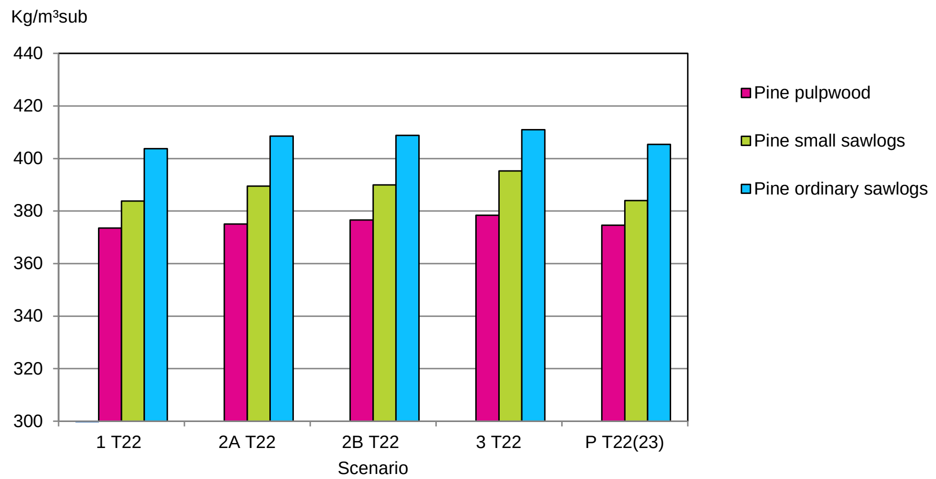


Figure 12.
Predicted basic density by product and scenario. Logs from simulated final felling on a T22 at latitude 64° and altitude 200 m.

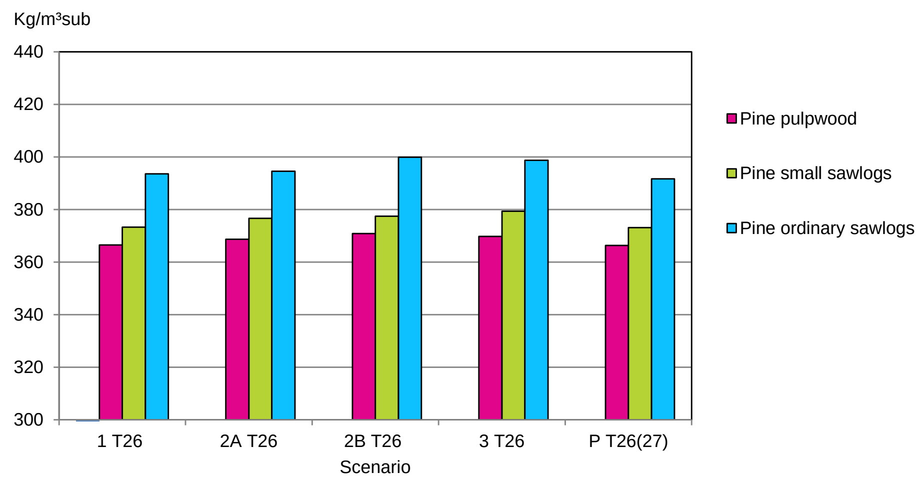


Figure 13.
Predicted basic density by product and scenario. Logs from simulated final felling on a T26 site at latitude 64° and altitude 200 m.

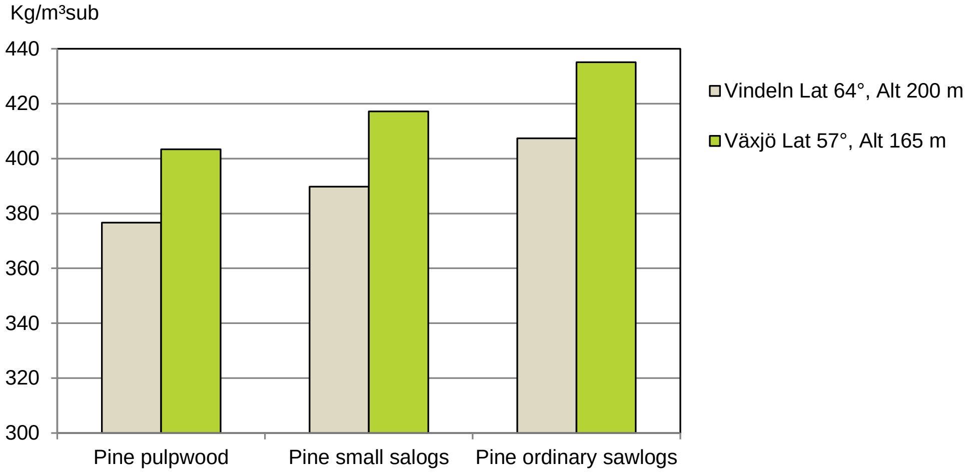


Figure 14.
Basic density kg/m$^3$sub. Comparison of predicted arithmetic averages of all scenarios from latitude 64°, altitude 200 m and latitude 57°, altitude 165 m respectively. Logs from simulated final felling.

# HARVESTING OPERATIONS AND COSTS

## Labor demand

All scenarios where the forests are managed for dense young stands are less labor intensive in the regeneration phase than when the stands are planted and conventionally managed, as the integrated scarification and mechanical seeding is faster than scarification and manual planting and also because there is less work in the PCT. Work hours per ha and 100 years are shown in Figure 15. Regardless of site index, the scenario with integrated scarification and mechanical seeding and base-line management has a low labor demand per ha and 100 years compared to the planted stand with standard management. The yield in the planted scenario is higher than in the direct seeding scenario and the labor demand per harvested m$^3$ in the two scenarios is equal (Figure 16).

Stands with standard silvicultural management (base-line) require less machine work per ha and 100 years than the stands managed for dense young stands, and therefore need less qualified labor (machine operators).

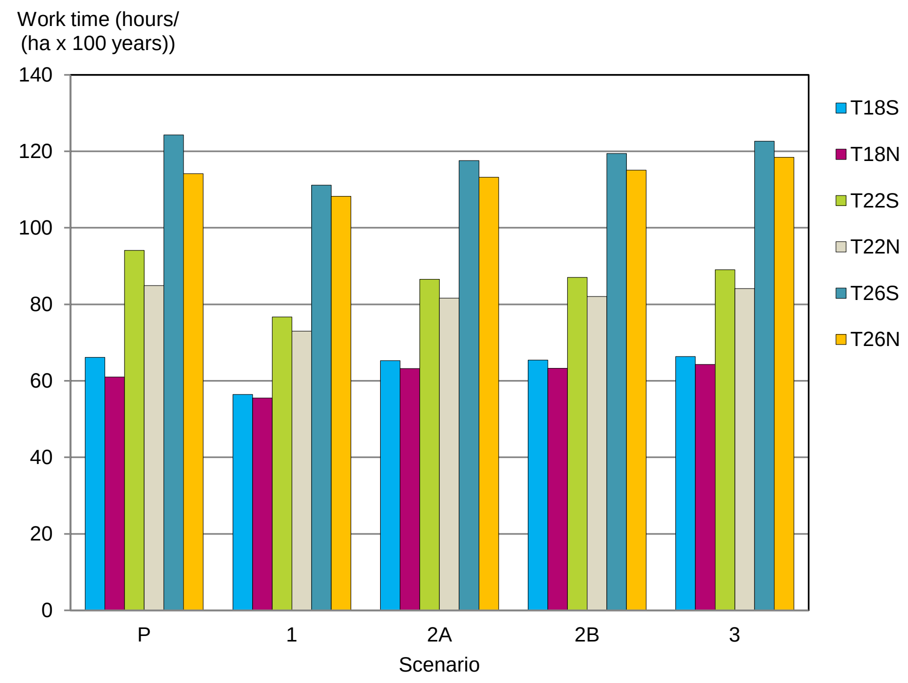


Figure 15.
Labor demand in hours per ha and 100 years for the scenarios.

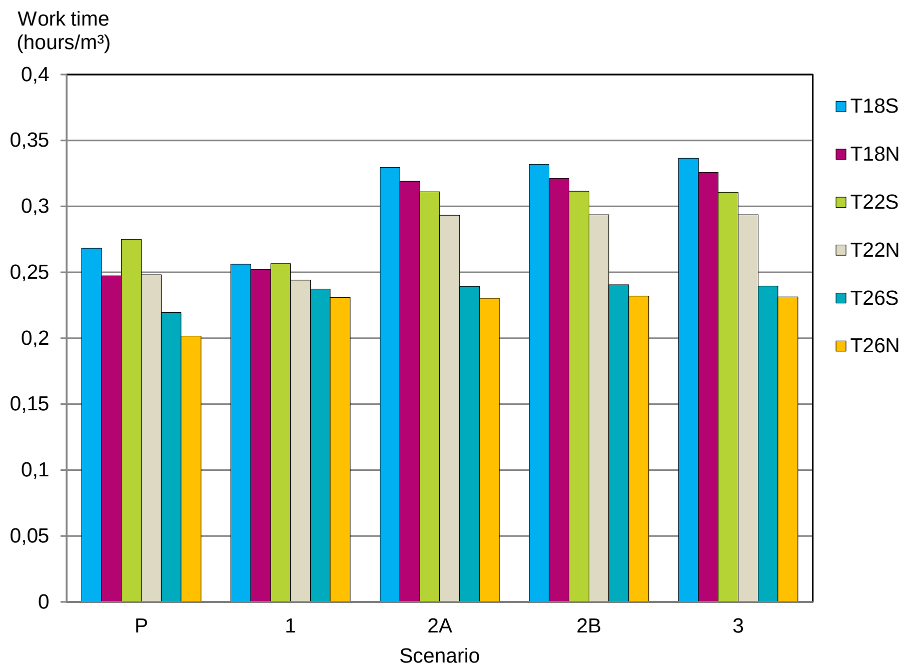


Figure 16.
Labor demand in hour per harvested $m^3$ of wood for the scenarios.

## Costs

### Costs of silvicultural activities

Regeneration costs are higher for the planted scenarios than for the scenarios that have been regenerated by mechanical seeding. For the scenarios with a normal management regime this is partly compensated for by a more expensive PCT in the dense stands. Compared to statistics of actual costs for precommercial thinning (Brunberg, 2012), the costs in all scenarios are low to moderate. This is because the PCTs in the simulations are carried out at the right time and the number of felled stems in each thinning is moderate, as two PCTs are carried out instead of just one.

### Commercial harvesting operations

The suggested management scenarios for dense young pine stands, particularly Scenario (2A), results in roundwood thinning operations that are dubious from a technical and cost perspective. The operations are hampered by low extracted volumes per ha and/or the small trees harvested, which lead to high costs for harvesting and forwarding of the wood. Furthermore, the relocation costs per harvested $m^3$ will also be high as an effect of the low volume harvested in each stand.

In addition, the early forest fuel thinnings are affected by low extraction levels of approximately 10 ton dry matter per ha. These low extraction levels cannot carry the costs of the harvesting operations and are therefore not profitable. However the calculations of harvesting costs in forest fuel thinnings are conservative, i.e. high, compared to the results of Iwarsson (Wide & Belbo, 2009) in their studies of actual operations. These studies show that there is a considerable development potential in the harvesting operations in small-diameter trees and potential to increase harvester productivity by 30 to 50 per cent compared to the functions used in the present study.

Final felling costs with a normal management regime are on the same level as the average costs reported by (Brunberg, T., 2012) for southern and northern Sweden. This suggests that the costs are somewhat overestimated, as the simulated stands have better harvesting conditions, i.e. they have higher stocks and the average tree size is somewhat larger than an average final felling stand.

## Roads and logistics

During a rotation period the number of harvesting operations is higher in the stands managed for forest fuel extraction from dense young stands, leading to more frequent use of roads and landings. In a larger perspective, there will be more stands harvested each year in a forest managed with dense young stands due to the increased intensity of treatment. This leads to an increased use of the road network, thereby increasing the costs of road maintenance. This is further increased if there is a demand that the same total volume should be harvested irrespective of the scenario in a forest area.

The logistical system will also be put under pressure by the management for forest fuel thinnings, which reduces the volume per product available on each landing at all subsequent logging operations, and thereby reducing the efficiency in the transports.

# ECONOMIC ANALYSES

## Soil expectation values

When we compare soil expectation values for the different scenarios, we find that the scenarios with high stem densities and early biomass harvest (2A and 2B) always have the lowest values. Scenario 3, also with high stem density but a slightly later biomass harvest, is somewhat better but always inferior to the best scenarios. In northern Sweden the best scenario is planting (P) on all sites while in southern Sweden direct seeding (1), and standard spacing is the best scenario on all sites.

Table 5.
Soil expectation values (SEK/ha) for the different scenarios calculated with 2.5 % interest rate.

| Scenario/Site | P | 1 | 2A | 2B | 3 |
|---|---|---|---|---|---|
| T18 North | –304 | –1 542 | –4 387 | –4 285 | –3 640 |
| T18 South | –5 362 | –2 861 | –5 514 | –5 416 | –4 480 |
| T22 North | 3 413 | 2 944 | –1 056 | –707 | 26 |
| T22 South | –2 819 | 1 311 | –2 432 | –2 027 | –656 |
| T26 North | 17 914 | 15 268 | 9 896 | 10 261 | 12 705 |
| T26 South | 10 965 | 13 619 | 8 624 | 9 093 | 12 241 |

## Sensitivity analyses – interest rate

The effect of varying interest rates on SEV is shown in Figures 17 and 18, representing the two most extreme sites. Intermediate sites show results between these two extremes. In southern Sweden direct seeding gave the highest SEVs for all interest rates. In northern Sweden planting gave the highest SEVs at interest rates below 3.0 – 3.5% and direct seeding at higher rates. In northern Sweden, the best scenario with dense spacing (3) reached the same SEV level as the base-line Scenario (1) at around 4% interest rate. In southern Sweden, Scenario (3) gave the highest SEVs at interest rates above 3.0 – 3.5%.

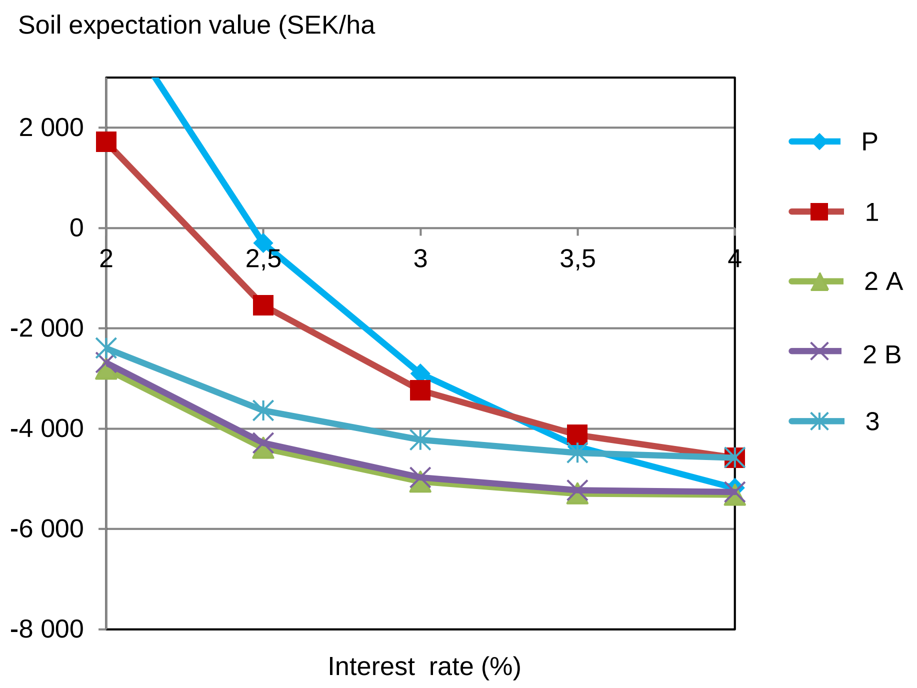


Figure 17.
Soil expectation values on a T18 site in northern Sweden for the different scenarios with interest rate varying between 2–4%.

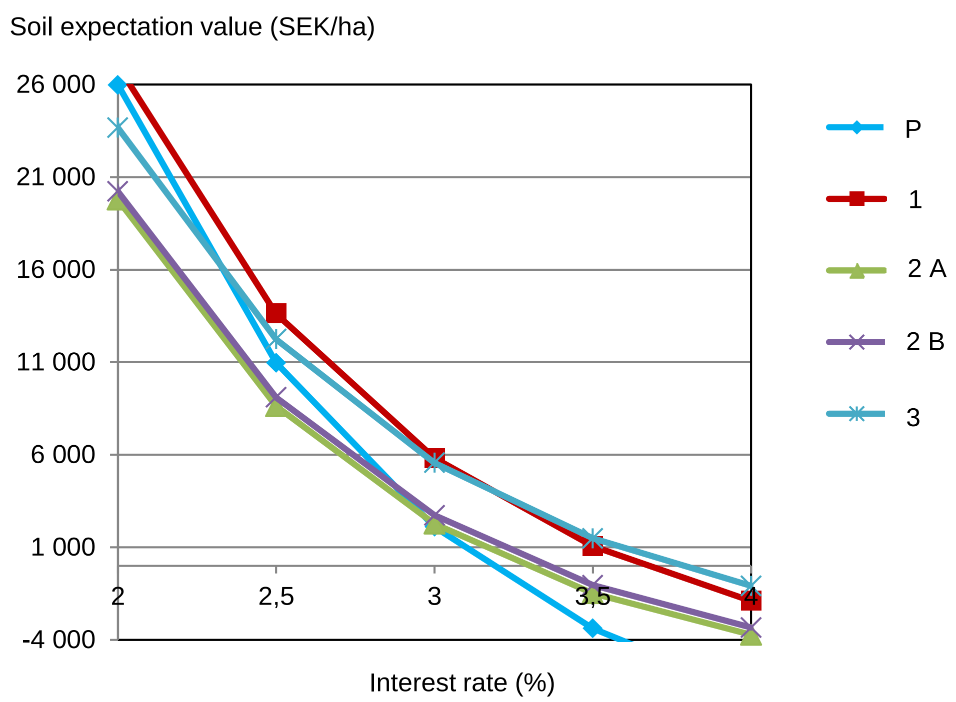


Figure 18.
Soil expectation values on a T26 site in southern Sweden for the different scenarios with interest rate varying between 2–4%.

## Sensitivity analyses – energy price

The effect of varying energy price on SEV is shown in Figures 19 and 20, representing the two most extreme sites. Intermediate sites show results between these two extremes. The energy price used as default was 202 SEK/MWh. At the poorest sites (T18) and on medium fertile sites in north Sweden (T22), the energy price must increase by 50 % or more to make the best dense-spacing Scenario (3) an economically better alternative than the base-line planting and direct seeding scenarios. At T22 in southern Sweden and T26 in northern Sweden, an increase in energy price of around 25 % would make the dense-spacing Scenario (3) a better alternative than the wide spacing. On T26 sites in southern Sweden, it takes an increase of only about 15% in energy price to make Scenario (3) economically better than the wide-spacing scenarios.

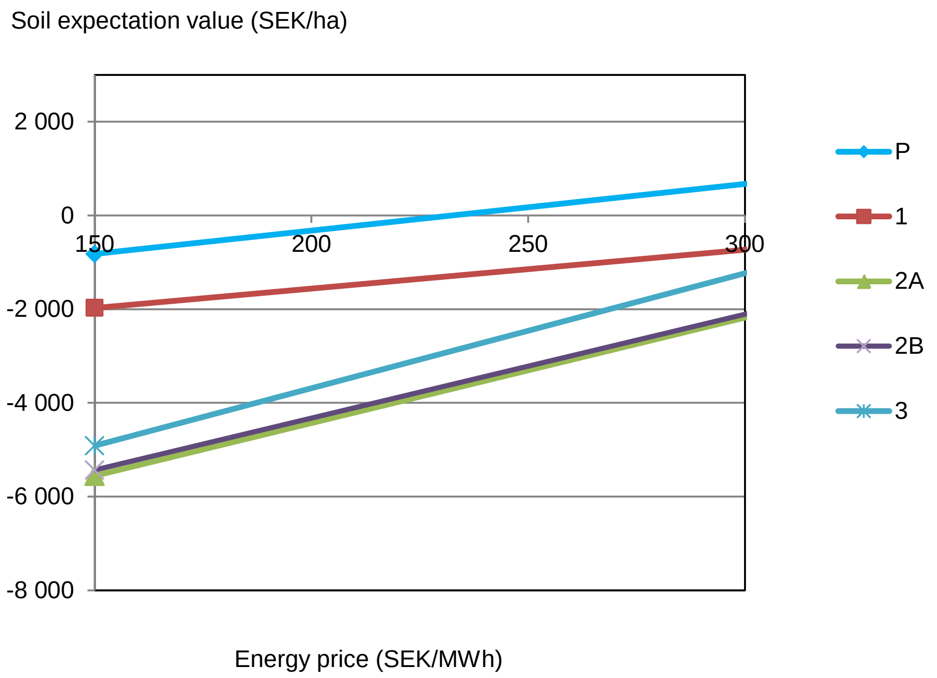


Figure 19.
Soil expectation values on a T18 site in northern Sweden for the different scenarios with energy price varying between 150–300 SEK/MWh.

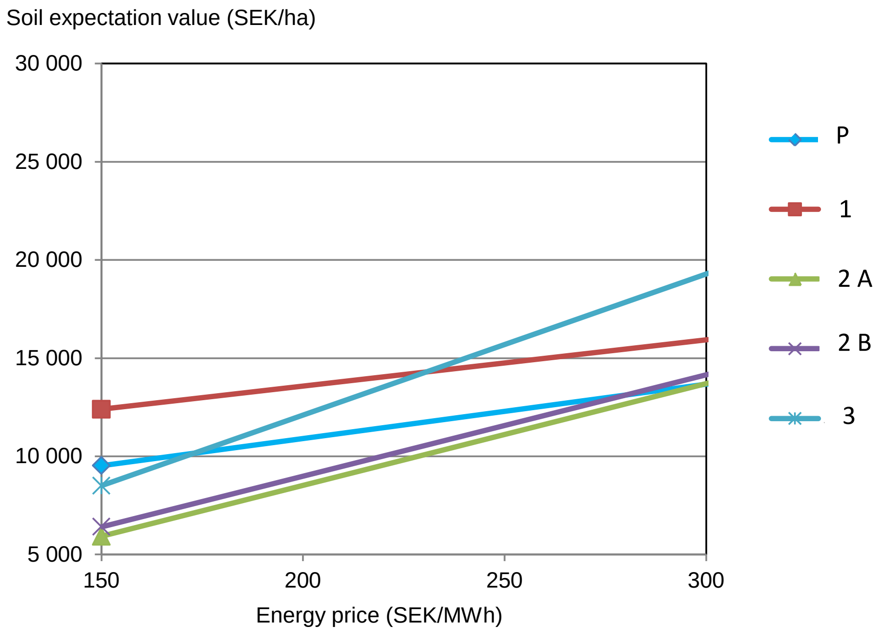


Figure 20.
Soil expectation values on a T26 site in southern Sweden for the different scenarios, with energy price varying between 150–300 SEK/MWh.

## Sensitivity analyses – harvesting cost for small trees

The effect of varying costs for the early biofuel harvest of small trees on SEV is shown in Figures 21 and 22, representing the two most extreme sites. Intermediate sites show results between these two extremes. The energy price used as default is set to 100% and varies down to 50% of the default. The analyses indicate how much we must reduce costs to make dense spacing the best alternative.

At the poorest sites (T18) and medium sites in northern Sweden (T22), the logging cost for small trees must be reduced by 50 % or more to make Scenario (3) better than the wide-spacing scenarios. On sites T22 in southern Sweden and T26 in the north, Scenario (3) becomes the most viable when logging cost for small trees is reduced by about 35 % and, on the best sites in southern Sweden (T26), a reduction of logging costs by 15–20 % will make Scenario (3) the best in economic terms.

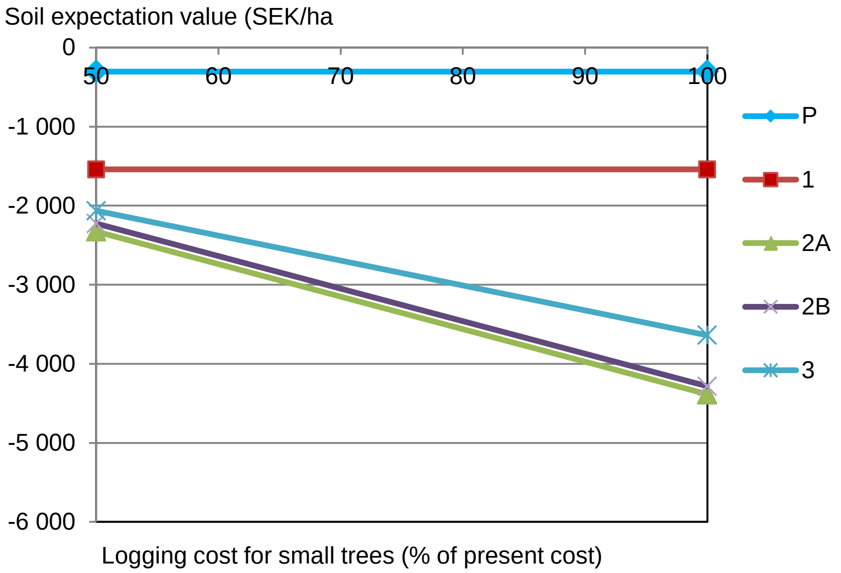


Figure 21.
Soil expectation values on a T18 site in northern Sweden for the different scenarios with logging costs for small trees varying between 50–100% of present costs.

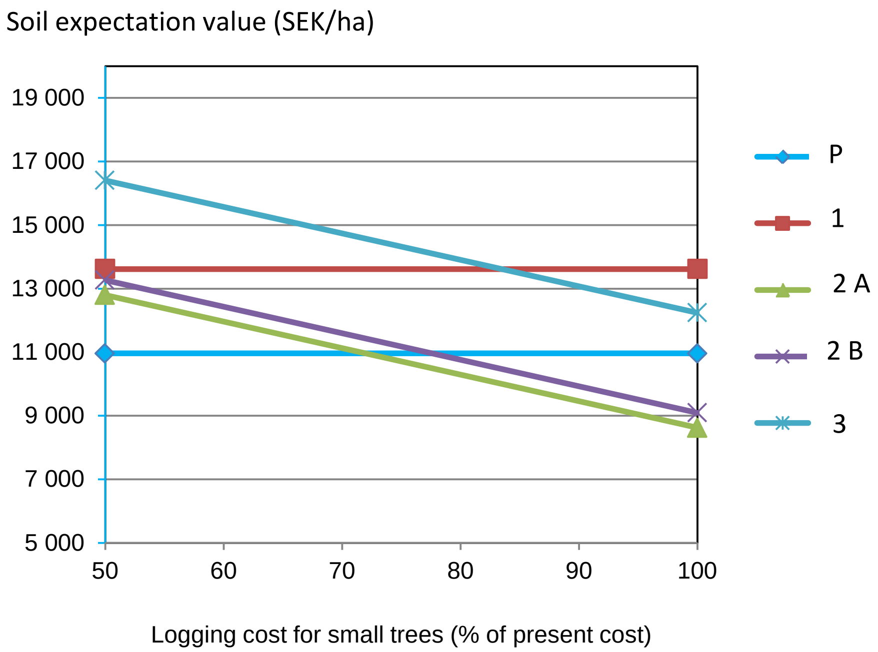


Figure 22.
Soil expectation values on a T26 site in southern Sweden for the different scenarios with logging costs for small trees varying between 50–100% of present costs.

# Discussion

## TIME AND COST FOR SILVICULTURAL AND HARVESTING WORK

### Reliability of the estimations and calculations

The calculations of time consumption for planting the new stand are a rough estimate based on actual prices paid for planting on a piece rate basis, and hourly work costs according to actual salary costs in accordance with labor agreements. This estimate seems to underestimate the time taken for the planting work, as the daily performance in planting seems too high. From a cost standpoint, the use of the planting cost based on the piece rate gives reasonable costs for planting, including the seedling cost. The calculated cost per ha for northern Sweden (2 200 seedlings/ha) is 4 510 SEK, which is close to the average cost of 4 430 SEK per ha reported by (Brunberg, 2012), and the cost of 10 375 SEK/ha (2 500 seedlings/ha) is close to Brunberg 10 530 SEK/ha average for southern Sweden.

Time consumptions for PCT, forest fuel thinning, roundwood thinning and final felling have all been calculated using the best available functions. However, the productivity norm for PCT is old and it was necessary to calibrate the calculations using the results from Ligné´s thesis. The conditions in the stand at the time of PCT has changed over the years and current stands are often a bit higher and denser given the average stand height compared to when the norm was made, so probably we are approaching the limits of where the norm is valid in today's PCT. However the simulated stands are closer to the stand characteristics that were common when the norm was made.

The time consumption norms for harvesters in conventional thinning and final felling or those for forwarders in thinning, final felling or residue extraction are all of a recent date, and so there are no reasons to suspect that there are any systematic deviations between estimated and actual time consumptions. The practice of thinning of small-diameter trees to extract biomass is growing fast. When the functions used are compared to recent studies of multi-tree handling harvesting with heads adapted to biomass harvesting, it can be seen that the productivities presented in the studies are substantially higher than those obtained by the functions under the same conditions. However, these time studies are only snap-shots of the harvesting productivities for a particular machine and driver combination in small research plots, while the functions used are based on follow-up studies of harvesting in multiple stands with many machines and drivers, and are therefore more likely to present an average productivity in thinning of dense young stands.

## Operational aspects in the different scenarios

The scenarios with a standard silvicultural management (base-line) give reasonable conditions for thinning operations with an acceptable economic result, regardless of site index and regeneration method. The planted stands generally have larger trees and a somewhat higher harvested volume than those regenerated by mechanical seeding. The harvested volume in first thinning is greater than 35 $m^3$ and the average stem volume between 0.05 and 0.07 $m^3$. Harvested volumes increase in the later thinnings as does the average stem volume, and when the mature stands are final-felled they are well stocked with a high average stem size, given the age and site index class.

Scenarios (2A and 2B) are problematic from an operational standpoint, as the forest fuel thinning is done at 10 m height of the dominant trees. As the thinning is done from below, i.e. the harvested trees are selected from the smaller trees, the harvested volume is small as is the average size of the harvested trees. Harvesting 10 ton DM per ha, equivalent to 23 $m^3$ per ha, with a basal area weighted mean diameter of approximately 8.6 cm results in a low performance level for the harvester and unacceptably high harvesting costs. In Scenario (2A), this is followed by a first round of wood thinning at the same stand age as in the base-line scenario, which results in another thinning with a to low harvested volume of small trees, thereby incurring high harvesting costs. In Scenario (2B) the first round of wood thinning is postponed by 5 years. This increases both the harvested volume and the average stem volume but, as they are still lower than in the base-line scenarios, the thinning operation will be more expensive. In both these scenarios, harvested volumes and the average size of the harvested trees will be lower in the subsequent thinnings and in the final felling than in the base-line scenario.

Scenario (3) results in a higher amount of extracted forest fuel, as the forest fuel thinning replaces the ordinary first round of wood thinning. However, as the stands have been allowed to grow with denser spacing, there are more trees to harvest than in the first round of wood thinning in the base-line scenarios; this increases time consumption for harvesting and thereby causes high harvesting costs. Although the following round of wood thinning take place at approximately the same time as the second round wood of thinning in the base-line scenario, harvested trees are as small as those harvested in the first roundwood thinning in the 'normal management' scenario and the harvested volume is lower. This results in a more expensive harvest operation and a lower income from the wood sale. Although the last thinning is comparable in both Scenario (3) and the base-line scenario, the final felling results in the harvested trees being smaller and lower harvested volumes per ha, which yet again reduces the economic outcome of Scenario (3). This can partly, but not completely, be mitigated by an increased rotation period for Scenario (3).

The fact that the average size of trees harvested is low in the forest fuel thinning can be found in the diameter limits for the merchantable trees. In a forest fuel thinning, a tree is considered merchantable if its dbh equals or exceeds 5 cm. In all other harvesting operations, this limit is 8 cm. A limit of 5 cm is too low to enable the harvester to reach a performance level high enough to make the thinning operation economically viable. It is not plausible that a harvester operator would choose to harvest such small trees except when they stand close to another tree that will be harvested. Consequently, it is likely that we have underestimated the size of the harvested trees and thereby overestimated harvesting costs in forest fuel thinnings.

## VALUATION AND CHARACTERIZATION OF WOOD PRODUCTION

The considerable effects on frequencies of different diameter classes of sawlogs from final fellings should be noted. Changes in flow of log sizes may lead to changes in future log pricing. To reach similar distributions of diameter classes from the alternative scenarios, the rotation time may be prolonged or shortened. However, such changes will also change the economic value of the produced sawlogs and also affect the flow of pulp and fuelwood.

The management effects on frequencies of stem faults and irregularities and effects on native wood characteristics might also affect the different scenarios. Such effects could not be evaluated in the scenario analyses but might be worth considering when decisions for alternative silviculture regimes are taken.

Product definitions and pricing for an unknown future market will always include considerable uncertainties. For this reason not only the economic but also the total volume and characterization figures may be considered. Whether differences in log sizes and internal properties will be equally or differently evaluated by future customers is subject for further analyses and discussions. Whatever the results will be of these types of analyses, predictable and reliable pictures of potential future flow of forest raw materials will be required.

## ECONOMIC ANALYSES

Our analyses indicate that, with the present systems, costs and prices and at interest rates commonly used by Swedish forest companies today, the most viable alternative is standard spacings after pre-commercial thinnings.

In northern Sweden, planting with genetically improved seedlings and standard PCT generated the highest soil expectation values. In southern Sweden, direct seeding gave higher SEVs than planting. This is on account of the higher cost of seedlings in southern Sweden due to their larger size. However, not all sites in southern Sweden fulfill the prerequisites for successful direct seeding results, so on many sites planting is the only viable option.

On the poorest sites (T18), even the best SEVs were negative. Natural regeneration under seed trees is commonly used to reduce regeneration costs and therefore improve SEVs on these kind of sites. A successful natural regeneration can also provide the necessary stem densities required to make management Scenarios (2A, 2B and 3) in this study possible.

Of the management alternatives with dense spacing, Scenario (3) had higher SEVs than Scenarios (2A and 2B) for all sites, interest rates, energy prices and logging costs tested. This indicates that, in dense young stands, it is better to wait until the normal height for first thinning. However, the increased risk of damage caused by snow and wind after thinning has to be considered. The dense spacings in Scenarios (2A, 2B and 3) generally reduced the diameter and basal area growth under the rest of the rotation. This resulted in lower volumes of sawlogs and pulpwood in later thinnings and final felling.

A main difference between northern and southern Sweden, besides seedling cost which only affects the planting Scenario (P), is the transport distance for biofuel from the forest to the energy plant. However there are forest areas close to energy plants even in northern Sweden and so the southern Swedish examples may better describe the situation.

Despite the higher SEVs for the wide-spacing alternatives, we conclude that there is a potential for the dense-stem scenarios, mainly Scenario (3), under certain circumstances, and especially if logging costs for harvest of small trees can be reduced by more than 15% and/or with slightly increased energy prices. The logging costs we have used represent average costs with present equipment and an average machine operator. The best machine/operator combinations already reach productivity that reduces the logging cost by more than 30%. We think the potential to reduce logging costs for small trees is great, both with improved machines and with proper training and selection of operators.

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APPENDIX 1

# BUCKING ANALYSES, CONDITIONS AND SETTINGS

**Table A1. Length and diameter limits by assortments and quality classes (QCL)**

| Pine | | Min Diam mm | Max DIam mm | Min Length cm | Max Length mm | Diameter class (mm) | Length class (cm) |
|---|---|---|---|---|---|---|---|
| 1 | QCL 1 Sawlogs | 180 | 750 | 370 | 580 | 180;200;220;240;250;260;280;300;320;340;360;380; | 370;400;430;460;490;520;550; |
| 2 | QCL 2 Sawlogs | 180 | 750 | 370 | 580 | 180;200;220;240;250;260;280;300;320;340;360;380; | 370;400;430;460;490;520;550; |
| 3 | QCL 3 Sawlogs | 180 | 750 | 370 | 580 | 180;200;220;240;250;260;280;300;320;340;360;380; | 370;400;430;460;490;520;550; |
| 4 | QCL 4 Sawlogs | 180 | 750 | 370 | 580 | 180;200;220;240;250;260;280;300;320;340;360;380; | 370;400;430;460;490;520;550; |
| 5 | Small sawlogs | 140 | 180 | 370 | 580 | 140;160;180; | 370;400;430;460;490;520;550; |
| 6 | Pulpwood | 50 | 999 | 270 | 580 | 50; | 270;310;340;370;400;430;460;490;520;550; |

| Birch | Min Diam mm | Max Diam mm | Min Length mm | Max Length mm | Diameter class (mm) | Length class (cm) |
|---|---|---|---|---|---|---|
| Pulpwood | 40 | 600 | 270 | 325 | 40; | 300; |

**Table A2. Bucking simulation settings and conditions. Frequencies of different wood quality classes and demarcation of relative heights, i.e. [%, distance from ground]/total height.**

**Pine**

| **Group** | **Share, %** | **Group A** | **Height, %** | **Group B** | **Height, %** | **Group E** | **Height, %** | **Group F** | **Height, %** | **Group G** | **Height, %** | **Group H** | **Height, %** | **Group I** | **Height, %** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Group A | 15 | Qclass 1 | 25 | Qclass 1 | 30 | Qclass 3 | 30 | Qclass 3 | 100 | Qclass 3 | 40 | Qclass 4 | 30 | Qclass 4 | 50 |
| Group B | 23 | Qclass 3 | 15 | Qclass 2 | 70 | Qclass 2 | 70 | Qclass | 0 | Qclass 4 | 60 | Qclass 2 | 70 | Qclass 3 | 50 |
| Group C | 0 | QQclass 2 | 60 | | | | | | | | | | | | |
| Group D | 0 | | | | | | | | | | | | | | |
| Group E | 30 | | | | | | | | | | | | | | |
| Group F | 10 | | | | | | | | | | | | | | |
| Group G | 10 | | | | | | | | | | | | | | |
| Group H | 7 | | | | | | | | | | | | | | |
| Group I | 5 | | | | | | | | | | | | | | |

**Table A4. K), Pricelists (SE target apportionments (%) and matrices for dimension limits by bucked assortments and quality classes)**

**Assortment: Sawlogs Qclass 1, Pine**
**Price matrix, SEK/m³sub**

| Length\Diam | **180** | **200** | **220** | **240** | **250** | **260** | **280** | **300** | **320** | **340** | **360** | **380** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **370** | 590 | 740 | 790 | 835 | 835 | 865 | 910 | 960 | 985 | 995 | 1005 | 1015 |
| **400** | 580 | 730 | 780 | 825 | 840 | 870 | 915 | 965 | 990 | 1000 | 1010 | 1020 |
| **430** | 610 | 760 | 810 | 855 | 850 | 880 | 925 | 975 | 1000 | 1010 | 1020 | 1030 |
| **460** | 600 | 750 | 800 | 845 | 865 | 895 | 940 | 990 | 1015 | 1025 | 1035 | 1045 |
| **490** | 645 | 795 | 845 | 890 | 875 | 905 | 950 | 1000 | 1025 | 1035 | 1045 | 1055 |
| **520** | 605 | 755 | 805 | 850 | 880 | 910 | 955 | 1005 | 1030 | 1040 | 1050 | 1060 |
| **550** | 650 | 800 | 850 | 895 | 890 | 920 | 965 | 1015 | 1040 | 1050 | 1060 | 1070 |

**Apportionment matrix, %**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 30 | 30 | 30 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 400 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 430 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 460 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 490 | 45 | 45 | 45 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| 520 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 550 | 10 | 10 | 10 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| **Totalt** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** |

**Accepted**
**Value loss** 1%

**Limitation matrix (M=manual only)**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 400 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 430 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 460 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 520 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Assortment: Sawlogs Qclass 2, Pine**

**Price matrix, SEK/m³sub**

| Length\Diam | **180** | **200** | **220** | **240** | **250** | **260** | **280** | **300** | **320** | **340** | **360** | **380** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **370** | 460 | 460 | 480 | 500 | 500 | 515 | 530 | 535 | 560 | 565 | 570 | 570 |
| **400** | 450 | 450 | 470 | 490 | 505 | 520 | 535 | 540 | 565 | 570 | 575 | 575 |
| **430** | 480 | 480 | 500 | 520 | 515 | 530 | 545 | 550 | 575 | 580 | 585 | 585 |
| **460** | 470 | 470 | 490 | 510 | 530 | 545 | 560 | 565 | 590 | 595 | 600 | 600 |
| **490** | 515 | 515 | 535 | 555 | 540 | 555 | 570 | 575 | 600 | 605 | 610 | 610 |
| **520** | 475 | 475 | 495 | 515 | 545 | 560 | 575 | 580 | 605 | 610 | 615 | 615 |
| **550** | 520 | 520 | 540 | 560 | 555 | 570 | 585 | 590 | 615 | 620 | 625 | 625 |

**Apportionment matrix, %**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 30 | 30 | 30 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 400 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 430 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 460 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 490 | 45 | 45 | 45 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| 520 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 550 | 10 | 10 | 10 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| **Totalt** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** |

**Accepted**
**Value loss** 1%

**Limitation matrix (M=manual only)**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 400 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 430 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 460 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 520 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Assortment: Sawlogs Qclass 3, Pine**

**Price matrix, SEK/m³sub**

| Length\Diam | **180** | **200** | **220** | **240** | **250** | **260** | **280** | **300** | **320** | **340** | **360** | **380** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **370** | 460 | 460 | 480 | 500 | 500 | 515 | 530 | 535 | 560 | 565 | 570 | 570 |
| **400** | 450 | 450 | 470 | 490 | 505 | 520 | 535 | 540 | 565 | 570 | 575 | 575 |
| **430** | 480 | 480 | 500 | 520 | 515 | 530 | 545 | 550 | 575 | 580 | 585 | 585 |
| **460** | 470 | 470 | 490 | 510 | 530 | 545 | 560 | 565 | 590 | 595 | 600 | 600 |
| **490** | 515 | 515 | 535 | 555 | 540 | 555 | 570 | 575 | 600 | 605 | 610 | 610 |
| **520** | 475 | 475 | 495 | 515 | 545 | 560 | 575 | 580 | 605 | 610 | 615 | 615 |
| **550** | 520 | 520 | 540 | 560 | 555 | 570 | 585 | 590 | 615 | 620 | 625 | 625 |

**Apportionment matrix**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 30 | 30 | 30 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 400 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 430 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 460 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 490 | 45 | 45 | 45 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| 520 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 550 | 10 | 10 | 10 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| **Totalt** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** |

**Accepted Value loss** 1%

**Limitation matrix (M=manual only)**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 400 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 430 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 460 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 520 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Assortment: Sawlogs Qclass 4, Pine**

**Price matrix, SEK/m³sub**

| Length\Diam | **180** | **200** | **220** | **240** | **250** | **260** | **280** | **300** | **320** | **340** | **360** | **380** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **370** | 390 | 410 | 410 | 410 | 410 | 410 | 415 | 415 | 415 | 415 | 420 | 420 |
| **400** | 380 | 400 | 400 | 400 | 415 | 415 | 420 | 420 | 420 | 420 | 425 | 425 |
| **430** | 410 | 430 | 430 | 430 | 425 | 425 | 430 | 430 | 430 | 430 | 435 | 435 |
| **460** | 400 | 420 | 420 | 420 | 440 | 440 | 445 | 445 | 445 | 445 | 450 | 450 |
| **490** | 445 | 465 | 465 | 465 | 450 | 450 | 455 | 455 | 455 | 455 | 460 | 460 |
| **520** | 405 | 425 | 425 | 425 | 455 | 455 | 460 | 460 | 460 | 460 | 465 | 465 |
| **550** | 450 | 470 | 470 | 470 | 465 | 465 | 470 | 470 | 470 | 470 | 475 | 475 |

**Apportionment matrix, %**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 30 | 30 | 30 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 |
| 400 | 0 | 0 | 0 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |
| 430 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 460 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 490 | 45 | 45 | 45 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| 520 | 0 | 0 | 0 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| 550 | 10 | 10 | 10 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 | 15 |
| **Totalt** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** | **100** |

**Accepted Value loss** 1%

**Limitation matrix (M=manual only)**

| Length\Diam | 180 | 200 | 220 | 240 | 250 | 260 | 280 | 300 | 320 | 340 | 360 | 380 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 370 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 400 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 430 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 460 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 490 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 520 | M | M | M | M | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 550 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

**Assortment: Small diam. sawlogs, Pine**

**Price matrix, SEK/m³sub**

| Length\Diam | **140** | **160** | **180** |
|---|---|---|---|
| **370** | 375 | 375 | 375 |
| **400** | 375 | 375 | 375 |
| **430** | 375 | 375 | 375 |
| **460** | 375 | 375 | 375 |
| **490** | 375 | 375 | 375 |
| **520** | 375 | 375 | 375 |
| **550** | 375 | 375 | 375 |

**Apportionment matrix, %**

| Length\Diam | 140 | 160 | 180 |
|---|---|---|---|
| 370 | 0 | 0 | 30 |
| 400 | 0 | 0 | 0 |
| 430 | 0 | 0 | 15 |
| 460 | 0 | 0 | 0 |
| 490 | 0 | 0 | 45 |
| 520 | 0 | 0 | 0 |
| 550 | 0 | 0 | 10 |
| **Totalt** | **0** | **0** | **100** |

| | |
|---|---|
| **Accepted Value loss** | 1% |

**Limitation matrix (M=manual only)**

| Length\Diam | 140 | 160 | 180 |
|---|---|---|---|
| 370 | 0 | 0 | 0 |
| 400 | M | M | M |
| 430 | 0 | 0 | 0 |
| 460 | M | M | M |
| 490 | 0 | 0 | 0 |
| 520 | M | M | M |
| 550 | M | M | M |

**Assortment: Pulpwood, Pine**

**Price matrix, SEK/m³sub**

| Length\Diam | **50 +** |
|---|---|
| **270** | 275 |
| **310** | 275 |
| **340** | 275 |
| **370** | 275 |
| **400** | 275 |
| **430** | 275 |
| **460** | 275 |
| 490 | 275 |
| 520 | 275 |
| **550** | 275 |

**Assortment: Pulpwood, Birch**

**Price matrix, SEK/m³sub**

| Length\Diam | **40 +** | |
|---|---|---|
| **270** | 0 | (Not bucked) |
| **300** | 270 | |

## Arbetsrapporter från Skogforsk fr.o.m. 2012

**2012**

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## SKOGFORSK

– Stiftelsen skogsbrukets forskningsinstitut

arbetar för ett lönsamt, uthålligt mångbruk av skogen. Bakom Skogforsk står skogsföretagen, skogsägareföreningarna, stiften, gods, skogsmaskinföretagare, allmänningar m.fl. som betalar årliga intressentbidrag. Hela skogsbruket bidrar dessutom till finansieringen genom en avgift på virke som avverkas i Sverige. Verksamheten finansieras vidare av staten enligt särskilt avtal och av fonder som ger projektbundet stöd.

## FORSKNING OCH UTVECKLING

Två forskningsområden:

- Skogsproduktion
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## UPPDRAG

Vi utför i stor omfattning uppdrag åt skogsföretag, maskintillverkare och myndigheter. Det kan gälla utredningar eller anpassning av utarbetade metoder och rutiner.

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