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# Synthesis report on utilization of peatland forests for biomass production

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[1]Luonnonvarakeskus

[2]Metsähallitus

# Synthesis report on utilization of peatland forests for biomass production

Sustainable Bioenergy
Solutions for Tomorrow

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Name of the report: Synthesis report on utilization of peatland forests for biomass production

Key words: *Betula pubescens*, drained peatlands, energy wood, Finland, forest management, low-productivity, *Pinus sylvestris*, profitability, simulation.

## Summary

This report presents the results of the studies carried out in BEST WP2, Task 2.1 “Raw materials” and its subtask 2.1.2.1, which focused on the utilization of peatland forests for biomass production. Nearly 5 million hectares of drained peatlands in Finland form a remarkable harvesting potential. Some of these areas have aroused interest as a possible resource for energy-wood harvesting, or on the other hand, as possible areas for peatland restoration because of unprofitability of the traditional forest management.

Chapter 1 provides the background for subtask 2.1.2.1. Chapter 2.1 first gives an overview of the characteristics and areal distribution of downy birch (*Betula pubescens*) dominated stands growing on drained peatlands. It then proceeds to present the results of a study, in which the yield and profitability of different management regimes and harvesting methods for birch stands were compared in 19 experimental stands. Chapter 2.2 presents the characteristics and areal distribution of such Scots pine (*Pinus sylvestris*) dominated stands on drained peatlands, where traditional forest management may not be feasible. Further, the harvesting potential of the three poorest drained peatland forest site types is analyzed by model-based, long-term scenario analysis. Chapter 2.3 examines cost-effective harvesting of low-productive peatland stands. Finally, chapter 3 presents the conclusions.

Based on Finnish National Forest Inventory data (NFI11, 2009-2013), the total area of birch-dominated stands on drained peatlands representing *forest land* was 572 000 ha. There were further 29 000 ha of birch-dominated stands on *poorly productive forest land*. Birch stands were most common in Northern Ostrobothnia - Kainuu region, and on the herb-rich site type of drained peatland forests. According to the study of the experimental stands, the most profitable management alternative was growing the stand without treatments and applying final cutting at a relatively high stand age, 50 years, or even later at 70 years if precommercial thinning had been applied at sapling stage. Harvesting both pulpwood and energy-wood poles as integrated harvesting in the final cutting resulted in the best profitability of the total management, whereas whole-tree energy-wood harvesting resulted in the lowest profitability, when prices, costs and productivity of up-to-date machinery was used. Thus, remarkable development in the productivity of the harvesting method, as well as higher prices of energy wood would be needed before the whole-tree method could become competitive with other harvesting methods in downy-birch stands.

Based on NFI11 (2009-2012) and according to set criteria, the total area of low-productive drained peatlands was 0.84 million ha, including 0.55 million ha of *poorly productive forest land* or *unproductive land*, where the recent Forest Act allows final cuttings without regeneration. The area of low-productive drained peatlands was largest in Northern Ostrobothnia - Kainuu and Lapland. Generally, the stand mean volume in these peatlands was less than 45 $m^3ha^{-1}$ and in many cases less than 15 $m^3ha^{-1}$, thus, harvesting may be feasible only in a minor part of these sites, even though clearcutting can be used. Profitable harvesting calls for a large area, short distances in haulage, and combining the low-productive area with a larger cutting area or timber trade agreement.

Concerning drained peatlands representing *forest land*, the three drained peatland forest site types that represent the lower end of the production-potential gradient sum up to an area of 1.8 million ha (NFI10). With the prices, costs, and final-cutting criteria used in the long-term simulations (100 years), an optimization analysis indicated that management aiming at harvesting of energy wood would be a better option for these sites than management aiming at producing pulpwood and sawlogs, especially in the northern part of the country (net present value with 2% interest rate). The average economical outcome per hectare improved when regeneration costs were avoided. Continuing timber management to the next tree generation was generally unprofitable. On the other hand, it was profitable to continue management for energy wood in the southern parts of the country, but only to use the present stands in the north.

The examination concerning harvesting showed that further growing of stands of low-productive peatlands decreases harvesting cost. Thus, there is no hurry with harvesting of these areas unless the stands are threatened by some damage.

## Contents

# 1 Introduction

In Finland, almost 5 million hectares of peatlands have been drained for forestry purposes. This activity, mainly during the 1960s and 1970s, has led to a significant increase in forest growth and volume. Total harvesting potential of timber (pulpwood and sawlogs) in peatland forests has been estimated as 9–12 million cubic meters annually (Nuutinen et al. 2007). A major part of the first post-drainage tree-generation stands has reached the maturity for the first commercial thinning. Some of these stands are well managed and highly stocked, some are in urgent need of silviculture due to neglected earlier care, and unfortunately, there are also low-productive, poorly stocked stands, where tree growth has not increased much after drainage.

The relatively high nitrogen content in peat makes peatlands potentially productive forest sites when drained (e.g., Westman and Laiho 2003). However, when compared to stands on mineral soils, drained peatland stands often have special features such as heterogeneity of stand structure, abundance of birch mixture, and instability of drainage conditions, which cause challenges to both forest management and harvesting. Traditional management of drained peatland forests aims at production of timber. However, the current view is that some stands might be more suitable for energy-wood production, depending on their location, site type, and stand structure. In that respect, the most interesting drained areas are firstly those with untreated, over-dense stands, especially the low-budget stands dominated by downy birch (*Betula pubescens* Ehrh.), and secondly the stands on low-productive areas, where active management is not economically profitable but where the existing stands could be harvested for energy.

In addition to the yield and harvesting removals, the profitability of forest management depends on the costs of silviculture and harvesting. On drained peatlands, ditch network maintenance is considered an essential treatment, and generally applied once or twice during rotation. Especially in stands dominated by Scots pine (*Pinus sylvestris* L.) on poorer site types, harvesting costs may be high due to the small harvesting removal and the small stem size. The costs can be decreased to some extent by carefully specifying the cutting areas. In practice, there are sometimes difficulties in identifying the profitably harvestable areas in the typically spatially clustered stands. In some of the poorest sites, it is obvious that investments for a new tree generation would not be profitable. In some of them, immediately applied clearcut for pulpwood or energy wood may be the only means to reach at least some economic gain.

In this report, we present the results of the studies carried out in BEST WP2, Task 2.1 “Raw materials”, subtask 2.1.2.1. This subtask focused on the utilization of peatland forests for biomass production. The general research questions were:

i) Can such peatland forests where timber production is not profitable be utilized as a new significant source of biomass?

ii) What are the management practices required in cost-efficient biomass production on these sites?

iii) What are the methods and technologies for profitable biomass recovery on peatlands?

In this report we introduce the main procedures and results grouped by the subject matter. The study of birch stands (chapter 2.1) concerned downy birch, which as a pioneer tree species very easily forms dense stands on drained peatlands, such stands being interesting objects for energy-wood harvesting. The study of low-productive peatland sites (chapter 2.2) concentrated on drained pine-dominated peatlands, especially on the poorest site types, where wood production potential is low, and energy-wood harvesting may be the only possibility for profitable management. Also the profitability of the management of a new tree-generation, a crucial question in the poorest site types, is discussed. Possibilities for cost-effective harvesting of low-productive peatlands are presented in chapter 2.3.

The abbreviations and definitions common for the study reports are presented in Tables 1-3.

*Table 1. Drained peatland forest site types.*

| Abbreviation | Name of site type[1)] | Abbreviations in Finnish[1)] |
|---|---|---|
| ClT | *Cladonia type* | Jätkg |
| DsT | *Dwarf shrub type* | Vatkg |
| VT1 | *Vaccinium vitis-idaea type I* | Ptkg I |
| VT2 | *Vaccinium vitis-idaea type II* | Ptkg II |
| MT1 | *Vaccinium myrtillus type I* | Mtkg I |
| MT2 | *Vaccinium myrtillus type II* | Mtkg II |
| HrT | *Herb-rich type* | Rhtkg |

[1)] according to Laine et al. 2012

*Table 2. Climatic regions used in the study, consisting of the former Forestry Centre areas. Collectively, S, W and E are called southern regions, and N and L northern regions, respectively.*

| Region | Former Forestry Centres involved |
|---|---|
| S: South | Ahvenanmaa, Rannikko (southern), Lounais-Suomi, Häme-Uusimaa, Kaakkois-Suomi |
| W: West | Rannikko (Ostrobothnia), Pirkanmaa, Etelä-Pohjanmaa, Keski-Suomi |
| E: East | Etelä-Savo, Pohjois-Savo, Pohjois-Karjala |
| N: North | Pohjois-Pohjanmaa, Kainuu |
| L: Lapland | Lappi (southern) |

*Table 3. Land classes.*

| Land classes | Annual increment of growing stock over the rotation |
|---|---|
| Forest land | $>1\ m^3ha^{-1}a^{-1}$ |
| Poorly productive forest land | $0.1–1.0\ m^3ha^{-1}a^{-1}$ |
| Unproductive land | $< 0.1\ m^3ha^{-1}a^{-1}$ |

# 2 Study reports

## 2.1 Birch-dominated stands on drained peatlands

Kojola, S., Niemistö, P., Ihalainen, A. & Laiho, R.

### 2.1.1 Introduction

Downy birch (*Betula pubescens* Ehrh.) is one of the most common tree species in Northern Europe. In Finland, it represents about 12% of the total stand volume. Downy birch tolerates moist conditions and thus grows well on wet mineral soils and drained peatlands. On peatland, it is often the first pioneer species after drainage, and may form dense thickets. Because of the relatively small size and low quality of the stems for sawlogs or veneer logs, downy birch stands typically only facilitate low-budget forestry.

Until now, the management of downy birch stands has aimed at production of pulpwood. Management guidelines have recommended tending young stands to 2000–2500 stems per hectare, and applying the first commercial thinning when stand dominant height has reached 13–15 meters. After thinning the density should be 12–13 $m^2$ or 1100 stems per hectare. However, downy birch has proved to respond only weakly to thinning (Niemistö 2013). Many low-diameter stems are also wasted in the traditional management, and thus the growing capacity of the site is not fully used. Thus, studies concerning alternative ways to manage downy birch stands are needed.

The aims of the study were i) to identify the total area, regional distribution, and stand structures of birch-dominated drained peatland sites, ii) to examine whether the management of these stands should be focused on energy-wood production rather than the traditional pulpwood production, and further, iii) to find the most profitable harvesting methods and optimal timings for the final cutting.

We identified the area and structure of the birch-dominated stands on drained peatlands using Finnish National Forest Inventory (NFI) -data. To find out what kind of management regimes would be the most productive for pulpwood and biomass, several downy birch stands were studied in long term experiments. The focus in our examination was in the key moments, when management decisions for the rest of the rotation are needed, and the most profitable ways for management should be found. Especially, we searched for an appropriate timing for final felling, both for pulpwood and energy-wood purposes.

The stands examined in this study represented the first tree generation after the initial drainage of peatlands. They were pure downy birch stands or mixed stands dominated by downy birch but with a pine (*Pinus sylvestris* L.) or spruce (*Picea abies* (L.) Karst.) admixture.

### 2.1.2 Material and methods

#### *2.1.2.1 Abundance of downy birch dominated stands on drained peatlands*

We used data from the Finnish National Forest Inventory (NFI11, measured in 2009-2013) for estimations of the total area and areal distribution of birch-dominated stands on drained peatlands. Only forestry land available for wood production was included. We classified these stands according to the total stand volume and the proportion of birch (<25, 25–50, 50–75, >75% of stand volume), and examined them by site types (Table 1) and climatic regions (Table 2). Any other deciduous trees present were counted in birch. We also used the NFI11 sample plots to get average descriptions of stand structures. Because downy birch very easily forms thickets to the sapling stands of conifers, the youngest development classes were ignored in these data, since they would not be managed as birch stands.

#### *2.1.2.2 Alternative management regimes and harvesting methods for downy birch stands on drained peatlands*

We studied the growth and yield as well as profitability aspects of management of birch stands on drained peatlands using data from a downy birch thinning experiment. The experiment was implemented by the Finnish Forest Research Institute (Metla) in 1975–1990, and it included 19 experimental stands located in Ostrobothnia and western Lapland (Regions W, N, and L, Table 2). The site types were MT2 or HrT (Table 1), representing relatively high levels of wood production potential. Temperature sum varied between 740 and 1080 d.d.. Based on the measurement data, we knew the actual development during 20–30 years for each treatment plot within stand (maximum 7 measurements, 5-year intervals). For a more detailed description of the experimental design see Niemistö (2013).

The measured variables included stand density (number of stems), basal area, dominant height, total volume and the volumes of the timber assortments (sawlogs, pulpwood, and waste wood), all separately calculated for the total tree stand, natural removal, harvesting removal, and the retained stand. We calculated the stand level results using KPL-software developed in Metla (Heinonen 1994), and the branch biomasses using biomass models of Repola (2008), transformed to solid cubic meters by the coefficient 2.0 (1 $m^3$ = 0.5 Mg).

We grouped the data by the **initial stage of the stands** and the first treatment applied at the onset of the experiments: precommercial thinning in sapling stand stage (**SS**), energy-wood thinning (**EW**), or pulpwood thinning (**PW**). The intensity of the first treatment varied from unthinned control plots to heavy thinning, following a randomized block design: on average, 40% of basal area was removed in PW, and 70–80% in EW and SS.

Over the remainder of the rotation for each stand, we considered three different **harvesting methods A–C** (Table 4). As merchantable wood, they included pulpwood, energy wood harvested as whole-tree including branches, and pulpwood plus energy wood as lopped poles obtained with integrated harvesting (Table 4). **Management regimes** (Table 5) were combinations of the first actual treatment applied in each stand (SS, EW, and PW) and the later treatments by alternative harvesting methods (A–C, table 4) and final-cutting ages. Different timing options were considered for the final cuttings (Table 5).

We then calculated the harvesting removals for all harvesting methods, for all actual thinnings and for final cuttings. Thinnings took place according to actual treatments applied at the experiments, whereas final-cutting removals were calculated for every measurement point (i.e. 5-year intervals). Thus, we were able to compare the removals and incomes for different time points of the final cutting.

For cutting incomes we used real roadside prices based on statistics (Metinfo 2014, Torvelainen 2014). Because of the generally poor quality of birch sawlogs from peatlands, all wood with diameter ≥ 6.5 cm over bark was considered as pulpwood, with the price of 30 € $m^{-3}$. Energy-wood price was 24 € $m^{-3}$ and 21 € $m^{-3}$ for lopped poles and whole-tree, respectively.

We calculated the harvesting costs using time consumption models, the volumes and structures of the removals, and unit costs of the work. We used for all cuttings the models of Laitila et al. (2014), who modelled thinning and clearcutting separately. For haulage of pulpwood we used the models of Kuitto et al. (1994), and for energy-wood components the models of Laitila et al. (2007). Government subsidies for energy-wood harvesting were not considered.

*Table 4. The alternative harvesting methods and the structure of the resulting removals (merchantable wood).*

| Harvesting method | | Pulpwood component | Energy-wood component |
|---|---|---|---|
| A. Pulpwood harvesting | Pulpwood | Pulpwood part of the stem[1)] | – |
| B. Integrated harvesting | Pulpwood + energy wood as lopped poles | Pulpwood part of the stem | Top waste[2)] + small stems[3)] - tops[4)] |
| C. Energy-wood harvesting | Energy wood as whole-tree | – | Large stems + small stems + branches - branch waste[5)] |

[1)] minimum top diameter of the pulpwood poles was 6.5 cm.
[2)] top waste = the part of the stem which is not pulpwood size.
[3)] small stems = stems smaller than pulpwood stems, diameter at breast height (d1.3) over 3.5 cm.
[4)] tops = the thinnest part of the stems cut away (diameter smaller than 2–3 cm).
[5)] branch waste = branches that were dropped at the cutting area.

*Table 5. Management regimes. Harvesting methods: see table 4.*

| Stand | First treatment (by varied intensities) | Final cutting | |
|---|---|---|---|
| | | Harvesting method | Age, years |
| SS | Precommercial thinning | A | 30, 40, 55 |
| | | B | 30, 40, 55 |
| | | C | 30, 40, 55 |
| EW | Integrated pulp & energy-wood harvesting (B) | A | 30, 40, 55 |
| | | B | 30, 40, 55 |
| | | C | 30, 40, 55 |
| PW | Pulpwood harvesting (A) | A | 55, 70 |
| | | B | 55, 70 |
| | | C | 55, 70 |

For the sapling stands (SS) we included the cost of precommercial thinning. The time consumption of precommercial thinning with clearing saw was based on the models of Kaila et al. (1999, 2001). We also included the cost of clearing in such cases, where only pulpwood was harvested in the final felling (method A), and a lot of small stems would thus remain in the cutting area. Due to that, clearing is needed before soil preparation and regeneration operations. Here, this cost was included in the costs of the present tree generation. For the time consumption of clearing, we used the model of Fernandez-Lacruz et al. (2013). We used the unit cost of 35 € $h^{-1}$ both for precommercial thinning and clearing.

We analyzed the profitability of the first thinning with net incomes, and the profitability of the total management regimes (covering the time from the decision point to the final cutting) with net present values (NPV). For NPV, incomes and costs were discounted to the decision point, here to the establishment of the experiments. For discounting, we used 0% (NPV0), 2% (NPV2), and 3% (NPV3) interest rates. Because of the large variation in the rotation lengths, we were not able to compare the different final-cutting timing options straightforward by NPV. Thus, we compared the profitability of different harvesting methods in two or three selected final-cutting ages (Table 5).

In this study the NPV method was considered adequate, when comparisons of thinning intensity and harvesting methods were concerned one final-cutting age at a time. However, it was obvious that NPV increases, when cutting removals increase over time. Therefore, we also calculated rough estimates of bare land values (BLV), making the assumption that after the final cutting of a birch stand, the area will be regenerated to spruce and managed according to the general management procedures for spruce. We used an average spruce stand, which was based on recently measured samples of young seedling stands. According to these measurements, a substantial mixture of downy birch will occur also in the future spruce stands, mainly because of summer frost damages in spruces, in line with our findings in a recently made NFI11-examination from western and northern Finland (unpublished). We then simulated the development of the spruce stand by the Motti-simulator (Hynynen et al. 2005, Salminen et al. 2005) and calculated the BLV. The

NPV of the present birch stands and the BLV of the following spruce generations were then combined, and used to roughly examine if and how the results (i.e. the ranking of the regimes) changed when bare land values were considered.

### 2.1.3 Results

#### *2.1.3.1 Downy birch dominated stands on drained peatlands*

On *forest land* (see table 3), the total area of birch-dominated stands was 572 000 ha (proportion of birch over 50% of stand volume). This area includes development classes from mature and thinning stands to advanced seedling stands: i.e., young seedling stands and seed tree stands are excluded. Furthermore, there were 29 000 ha on *poorly productive forest land* (see table 3). Birch-dominated stands were most common in the North region (Fig. 1). A major part of the stands were HrT sites, but birch was common also on the site types MT2 and VT2 (Fig. 1).

The stand mean volumes of the birch-dominated stands on *forest land* varied from 28 to 144 $m^3ha^{-1}$, as average by site types and regions (Table 6). Almost 65% of the stands were relatively mature and highly stocked (stand volume >75 $m^3ha^{-1}$) (Fig. 2): in this volume class the stand mean volumes were 90–190 $m^3ha^{-1}$, depending on region and site type. Stand mean diameter, reflecting stem size that is an important variable in cost-efficient harvesting, varied between 8 and 18 cm, as average by site types and regions (Table 6). In highly stocked stands, mean diameter was the highest with a relatively low proportion of birch. In contrast, in younger stands and stands with smaller stems, mean diameter was highest in pure birch stands (birch proportion >75%). The result indicates that downy birch is a dominant tree species in young or low-volume stands. Later with increasing total volume, conifers in mixed stands are larger than downy birches (Fig. 3). Based on the NFI-data, the total volume of the growing stock on birch-dominated drained peatland is close to 60 million $m^3$. According to Niemistö and Korhonen (2008), approximately three quarters of that can be expected to be birch wood.

*Table 6. Average of stand mean diameter (d1.3, cm) and average of stand mean volume of the growing stock ($m^3ha^{-1}$) in birch-dominated stands (proportion of birch over 50% of stand volume), by site types and climatic regions. Young seedling stands and seed tree stands excluded. Site types: see Table 1, regions: see Table 2.*

| | S | | W | | E | | N | | L | |
|---|---|---|---|---|---|---|---|---|---|---|
| | D | Vol | D | Vol | D | Vol | D | Vol | D | Vol |
| HrT | 18 | 142 | 16 | 115 | 16 | 112 | 15 | 94 | 12 | 86 |
| MT2 | 17 | 144 | 16 | 132 | 14 | 113 | 15 | 105 | 11 | 65 |
| MT1 | 14 | 140 | 15 | 118 | 15 | 122 | 13 | 98 | 14 | 102 |
| VT2 | 8 | 61 | 15 | 106 | 12 | 99 | 13 | 83 | 8 | 67 |
| VT1 | 16 | 125 | 16 | 129 | 12 | 70 | 12 | 72 | 12 | 69 |
| DsT | - | - | 14 | 90 | 16 | 118 | 10 | 38 | 10 | 28 |

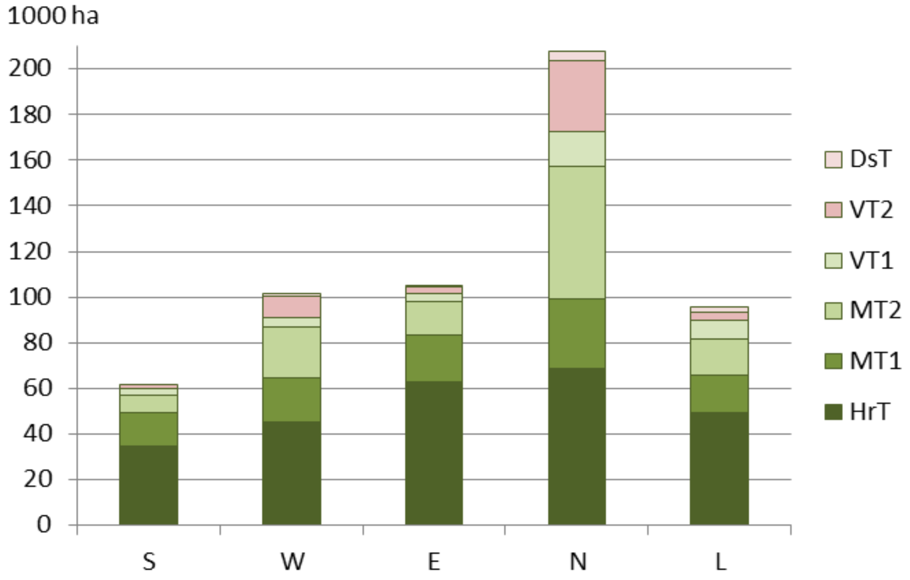

*Figure 1. Area of birch-dominated stands (proportion of birch over 50% of stand volume) on forest land, by drained peatland forest site types and climatic regions. Young seedling stands and seed tree stands are excluded. Site types: see Table 1, regions: see Table 2.*

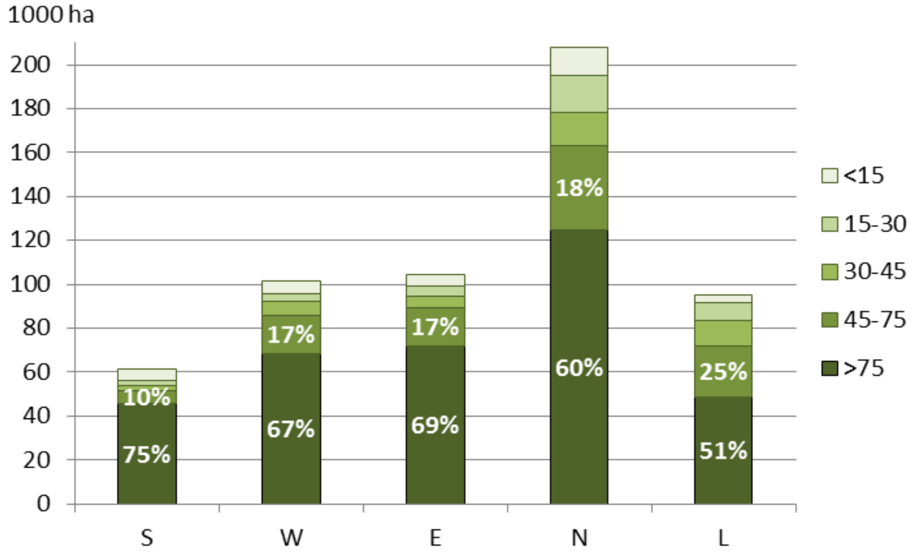

*Figure 2. Area of birch-dominated stands (proportion of birch over 50% of stand volume) on forest land, by volume classes (volume of the growing stock, $m^3ha^{-1}$) and climatic regions. Young seedling stands and seed tree stands are excluded. Regions: see Table 2.*

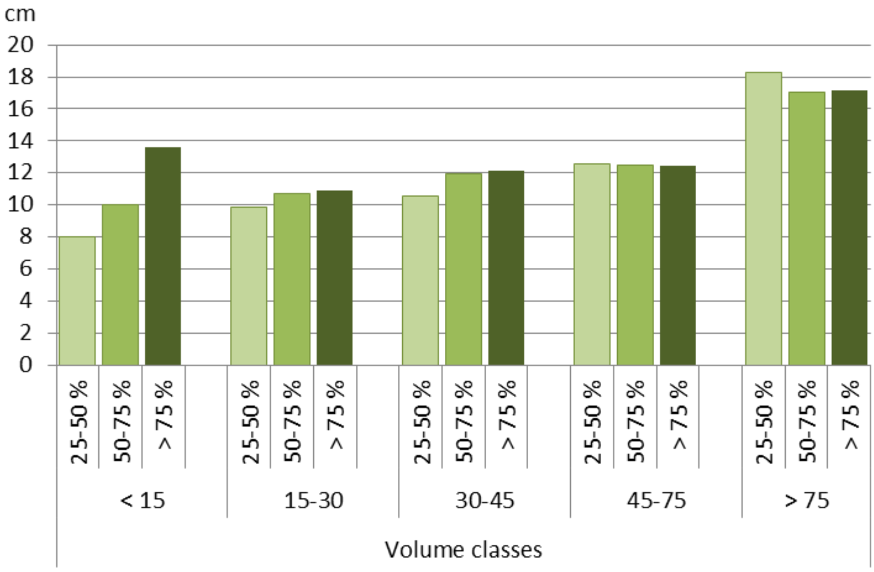

*Figure 3. Mean diameter of drained peatland stands with different proportions of birch, by volume classes. Young seedling stands and seed tree stands excluded.*

### *2.1.3.2 Alternative management regimes - effects on the yield of merchantable wood at different stand ages*

In the previous chapter, we presented general estimates of the area and structure of birch stands on drained peatlands based on NFI. The following results are based on a study of experimental stands including a wide range of thinning intensities and a wealth of growth data from sapling stands to mature stands. These stands covered well the variation existing in the most common site types of downy birch dominated stands, especially in western and northern Finland.

In 30-year management regimes, potential cutting removals of merchantable wood, especially the removals of pulpwood-sized trees, remained low. Depending on the intensity of the first treatment, the average removals varied from 20 to 100 $m^3ha^{-1}$ pulpwood and from 50 to 140 $m^3ha^{-1}$ whole-tree energy wood, respectively (Fig. 4). Maximum mean annual yields of different types of merchantable wood (pulpwood, poles, whole-tree) varied from 1.0 to 4.6 $m^3ha^{-1}a^{-1}$ (Table 7).

Among the 30-year management regimes, total removals were the highest in very lightly thinned EW-stands (Fig. 4). Very light thinning resulted in even higher removals than neglecting thinnings, which was probably due to the higher mortality of the smallest stems and the shrinking of the crowns of bigger trees, when thinning was not applied. Total removals were clearly lower in SS- than in EW-stands (Fig. 4). This was partially due to the small stems felled in precommercial thinning and thus excluded from the removals. When unthinned plots were compared, the removals including small stems differed only slightly between SS- and EW-stands, whereas in pulpwood regimes the difference was large in favour of EW-stands. This was probably due to the higher density and more northern location of the SS-stands (site index H50 according to dominant height at the age of 50 years being 14.4 in SS-, and 16.0 in EW-stands, respectively).

Among the 40-year management regimes, maximum yields varied from 2.3 to 4.4 $m^3ha^{-1}a^{-1}$ (Table 7). Unthinned SS-stands reached the same level of total removals as EW-stands (90–170 $m^3ha^{-1}$ on average, Fig. 4). Pulpwood removal was still slightly larger in EW-stands. In SS-stands, pulpwood removal was larger in unthinned than in thinned stands, the total being on average half of the removals of whole-tree energy wood. In both SS- and EW-stands the effect of thinning intensity on total removals followed similar patterns in the 30- and 40-year regimes, except that in EW-stands the normal thinning intensity overtook the heavy intensity thinning, and the removals of whole-tree in unthinned stands almost reached those of the lightly thinned stands.

Among the 55-year management regimes, unthinned SS-stands were still the most productive and produced more both stemwood (210 $m^3ha^{-1}$) and whole-tree energy wood (240 $m^3ha^{-1}$) than any other stand (Fig. 4). The removals in PW stands were lower than those in EW-stands or the densest SS-stands (Fig. 4). This was probably due to the removal lost in precommercial thinning and the decreased volume increment at young stand stage caused by uncommercial thinning.

When the management regimes were still extended up to 70 years, unthinned PW-stands reached the largest removals regardless of the harvesting method (Fig. 4). However, mean annual yields were only 2.7–3.2 $m^3ha^{-1}a^{-1}$ (Table 7).

*Table 7. Maximum yields (mean annual increment of merchantable wood, $m^3ha^{-1}a^{-1}$), by different rotation lengths.*

| Harvesting method in final cutting | Stand and rotation, yrs | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | SS, 30 | SS, 40 | SS, 55 | EW, 30 | EW, 40 | EW, 55 | PW, 55 | PW, 70 |
| A. Pulpwood | 1.0 | 2.3 | 2.7 | 3.4 | 3.4 | 3.4 | 2.4 | 2.7 |
| B. Integrated / lopped poles | 2.9 | 3.8 | 3.9 | 4.2 | 4.0 | 3.7 | 2.7 | 2.9 |
| C. Energy wood / whole-tree | 3.5 | 4.4 | 4.4 | 4.6 | 4.4 | 4.0 | 3.0 | 3.2 |

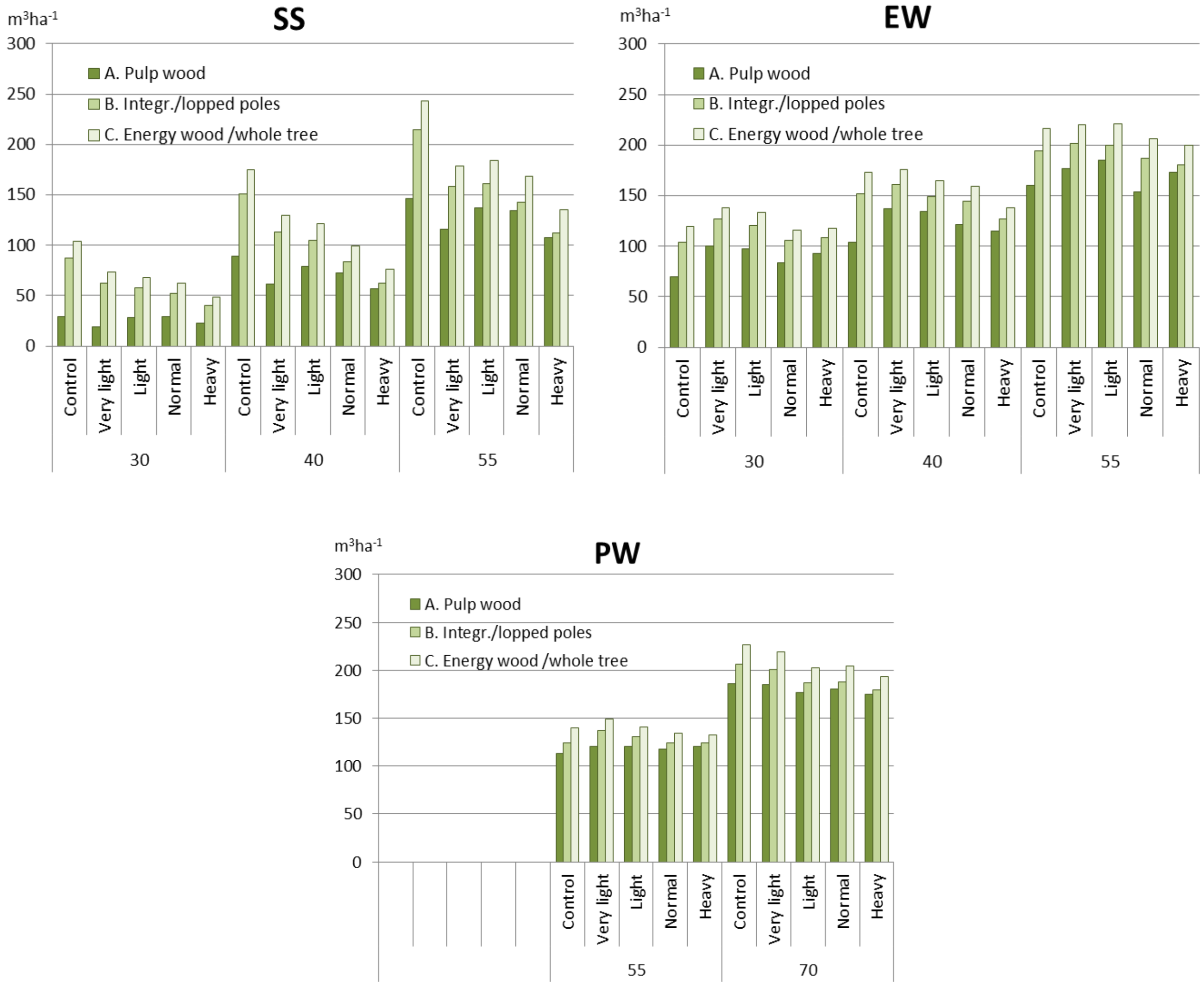

*Figure 4. Average total removals in alternative management regimes. The first treatment of SS-stand was precommercial thinning (no removal). X-axis: intensity of the first thinning, and stand age at final-cutting time. Harvesting methods: see Table 4, management regimes: see Table 5.*

### *2.1.3.3 Alternative management regimes - effects on profitability*

#### SS-stands (sapling stand stage)

These results are valid for situations where the decision-chain started from the stage of sapling birch stand. In SS-stands, the first treatment, precommercial thinning, causes costs only. The costs vary according to stand density and the stump diameter of the felled trees. In very dense birch thickets the cost can be very high. To eventually get profit from precommercial thinning, the cost should be covered by the better growth of the retained trees. Although the volume of the felled stems in some of the precommercial thinnings, at least with normal or heavy intensity, seemed to be large enough for energy-wood harvesting (Fig. 5), the profitability of the harvesting would have been negative, and resulted in higher total costs compared to precommercial thinning.

The profitability of the total management regimes, covering the time from the decision point to the final cutting, depended on the intensity of the first treatment, timing of the final cutting, and the interest rate used in discounting. Regimes with final cutting at the age of 30 years were all unprofitable and resulted in negative NPV regardless of the harvesting method or interest rate applied (Fig. 6). At the age of 40, NPV2 reached a positive value for pulpwood harvesting as final cutting in unthinned stands, and just barely positive values when precommercial thinning had been light or moderate. At final-cutting ages of 40–55 years, most combinations of harvesting methods and stand densities resulted in positive NPV (Fig. 6), and the integrated harvesting became competitive in lightly or moderately first-thinned stands.

The most profitable management regime and harvesting method for SS-stands was growing without thinnings, which resulted in NPV2 of -300, 450 or 1050 € ha$^{-1}$ at rotation lengths 30, 40 or 55 years, respectively (Table 8). In the cases where thinning was applied, very light intensity yielded the lowest profitability (NPV2) (Fig. 6). Interest rate had only minor effect on the ranking of regimes that involved different thinning intensities.

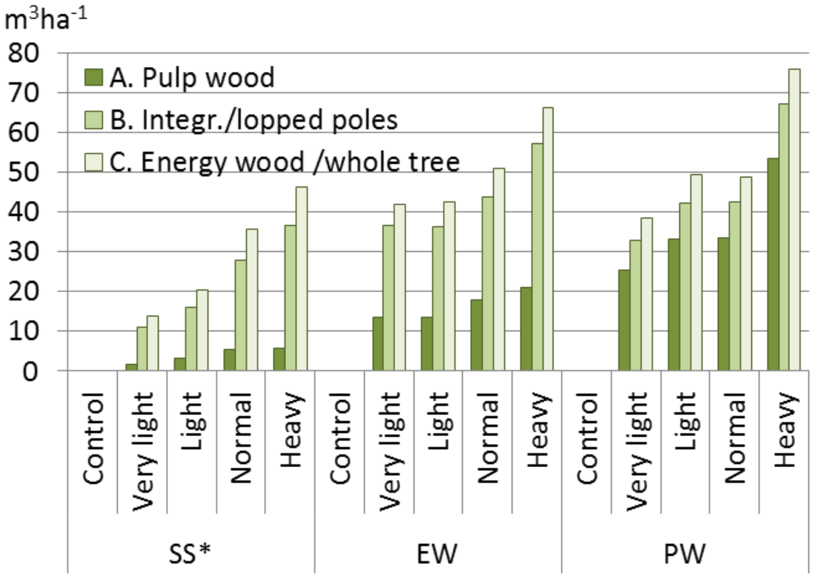

*Figure 5. Average first thinning removals by alternative harvesting methods and thinning intensities. Removals obtained with other methods than those actually applied in the stands are computational, as in the SS-stands, where the removal was based on the size of the removed trees in precommercial thinning. X-axis: thinning intensity and stand group. Harvesting methods: see Table 4.*

### EW-stands (energy-wood thinning stage)

The results of EW-stands are valid for young birch stands where energy-wood thinning may be actual. On average, the removals of the first thinnings with light intensity were about 65% of those of the heavy thinnings (Fig. 5). Removals including energy wood were on average three-fold compared to pure pulpwood removals (Fig. 5).

Growing without first thinning was the most profitable management regime in EW-stands, with all studied final-cutting ages (30, 40 or 55 years). Among these unthinned stands, pulpwood harvesting in final cutting was the best harvesting method in the 30- and 40-year management regimes, although the clearing cost of small stems was included in NPV, whereas in the 55-year management regime, pulpwood harvesting and integrated harvesting were equally profitable.

The first thinning operation as such was considered profitable when net incomes were positive. However, in EW-stands, net incomes of the first thinning were generally negative. For example, the incomes from the first integrated harvesting varied from 950 to 1500 € ha$^{-1,}$ and the harvesting costs from 2150 to 3250 € ha$^{-1}$, depending on the thinning intensity. Thus, in some cases, precommercial thinning by clearing saw would have been a more preferable treatment than harvesting.

Profitability of the total management regimes was generally negative when thinning was applied. As late as final-cutting age of 55, and with light or normal thinning intensity, the profitability (NPV2) of the total regime just barely reached a positive value for pulpwood and integrated harvesting (Fig. 6). Whole-tree energy-wood harvesting in final cutting resulted in clearly negative NPV, and was the most unprofitable method. The heavier the first treatment was the lower was NPV. In very light thinning, however, NPV was low like it was in SS-stands. The reason for this may be the high number and expensive harvesting of the very small stems that were abundant in the total removal of this regime.

Growing without thinning and using the most profitable harvesting method for EW-stands, the highest NPV2 was 500, 800 or 1400 € ha$^{-1}$ for rotation length 30, 40 or 55 years, respectively (Table 8). The lowest NPV2 was reached in heavily thinned stands where it was negative in all cases.

The yield of the EW-stands was best utilized with very light thinnings, because thus the lowest number of useful stems was missed. Also, practically no growth losses took place because the stem number was relatively high after light thinning. Therefore, it was useful to study more closely the effects of thinning intensity just in EW-stands. Heavy thinning decreased the total harvesting potential of whole-tree removal by 20, 38 or 21 m$^3$ha$^{-1}$ (Fig. 4), when the final cutting took place at age of 30, 40 or 55 years, respectively. The relative decline from maximum was 15, 21 or 9%, respectively. The effect of moderate thinning was 16, 9 or 6%, respectively. The negative effect of heavy thinning on the cutting potential of pulpwood was smaller compared with that of whole-tree energy wood: 7, 22, and 12 m$^3$ha$^{-1}$ at the respective ages above.

### PW-stands (pulpwood thinning stage)

In PW-stands the decision-chain started with traditional pulpwood harvesting as first thinning. The stands being more mature than the previous, most of the trees had already reached the size of pulpwood logs. Thus, the energy-wood removal could have been only slightly higher than that of pulpwood harvested in the first thinning (Fig. 5). The average first thinning removal was 33 $m^3ha^{-1}$ of pulpwood in light and normal thinnings and on average 60% larger in heavy thinnings (Fig. 5).The lopped poles and branches increased removals by 8 $m^3ha^{-1}$ both. Because these stands had mostly been tended as sapling stands before the establishment of the experiment, there were few small stems left at the time of both thinning and final felling. The harvesting costs of the first thinning varied between 400–1200 € $ha^{-1}$ depending on the total removal and stem size. Incomes varied from 800 to 1600 € $ha^{-1}$. On average, net income of the first thinning was positive.

The profitability of the different management regimes varied only little in PW-stands (Fig. 6, Table 8). When final cutting took place at 55 years, it was not reasonable to compare thinning intensities at all, because there would have been only a short increment period, or none, after the thinning operation. Somewhat unexpectedly, the unthinned control was a well-competitive regime still at 70 years (Fig. 6), even though natural removal was increased.

With an increasing interest rate, the regimes including light or moderate thinnings became more profitable. However, the effect of thinning intensity on NPV was minor. In PW-stands, a rotation period longer than 55 years was more profitable irrespective of the interest rate used (2% or 3%).

To complement the NPV analysis we made a rough estimation of bare land values (BLV) based on the assumption that birch stands would be regularly regenerated to spruce. The NPV of present birch stands and the BLV of the following spruce generations were then combined. This sum ($NPV_{birch}$ + $BLV2\%_{spruce}$) gave mainly the same ranking of regimes as the NPV results of the birch stands. At the interest rate of 3%, BLV would have been negative.

*Table 8. Net present values (NPV, interest rates 2% or 3%) by different rotation lengths obtained with the most appropriate management regimes and harvesting methods for each stand group.*

| Rotation, yrs | NPV2 | | | NPV3 | | |
|---|---|---|---|---|---|---|
| | SS | EW | PW | SS | EW | PW |
| 30 | -300 | 500 | | -300 | 450 | |
| 40 | 450 | 800 | | 350 | 700 | |
| 55 | 1050 | 1400 | 1750 | 800 | 1100 | 1700 |
| 70 | | | 2200 | | | 1900 |

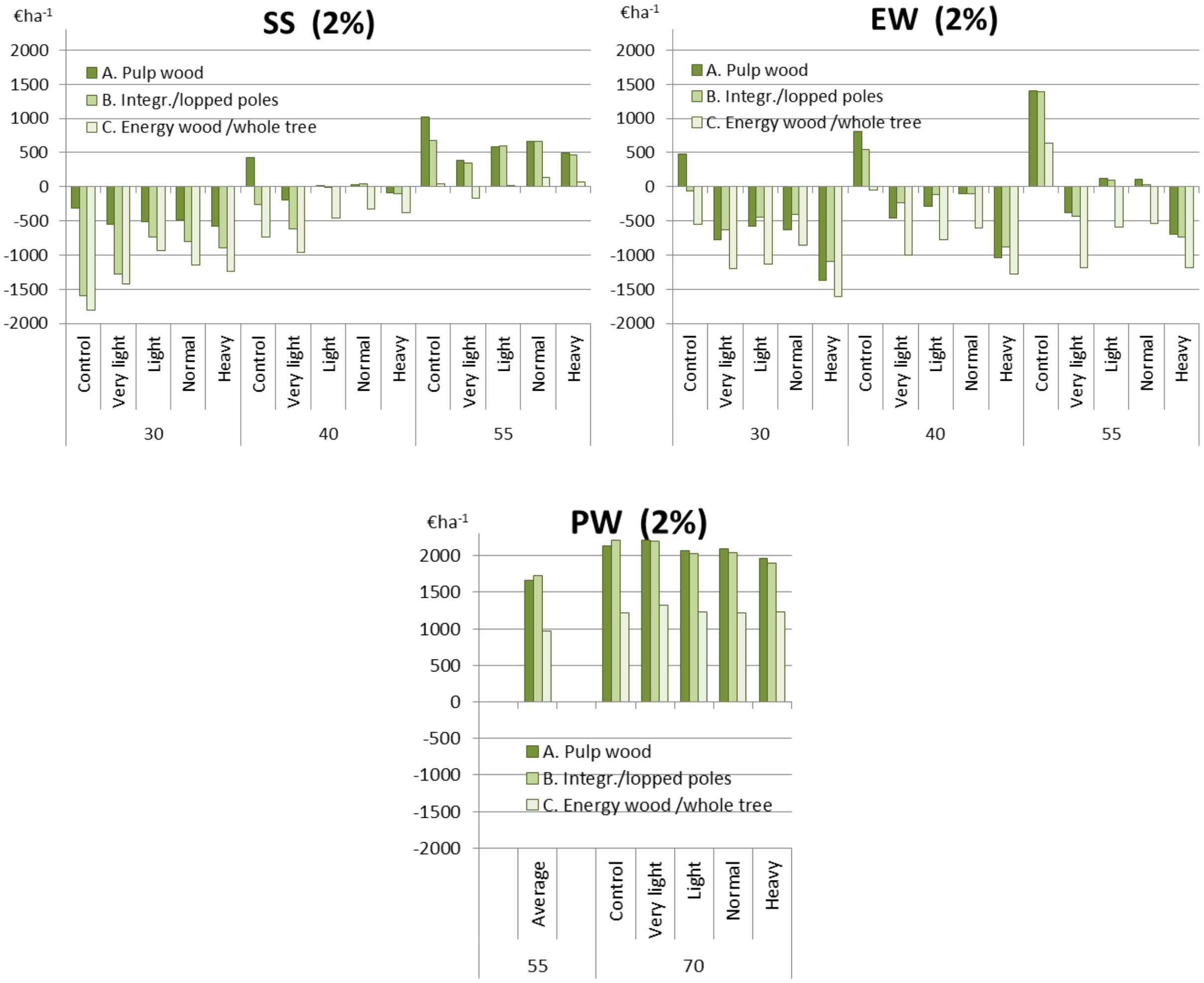

*Figure 6. Average net present values (NPV2) in alternative management regimes. X-axis: first thinning intensity and stand age at final-cutting time. Harvesting methods: see Table 4, management regimes: see Table 5.*

*Stand groups: SS = sapling stand stage, EW = energy-wood thinning stage, PW: pulpwood thinning stage, according to mean height of the stands at the time when the experiment was established.*

## Impacts of harvesting costs and energy-wood prices on profitability

The whole-tree energy-wood harvesting (method C) proved to be a clearly less profitable harvesting method than the others examined here, in all cases. Method C caused 900–1000 € ha$^{-1}$ lower income compared with the other methods, under the prices and other principles as settled in this study. To find out the principal reasons for this pattern, we examined more closely the components of the incomes and costs in two example stands. The stands represented average results of **the stand groups SS and EW, with final cutting at 55 years.** Having equal first treatments (SS: precommercial thinning, EW: integrated thinning) the differences between harvesting methods would be caused by the final cuttings (Fig. 7).

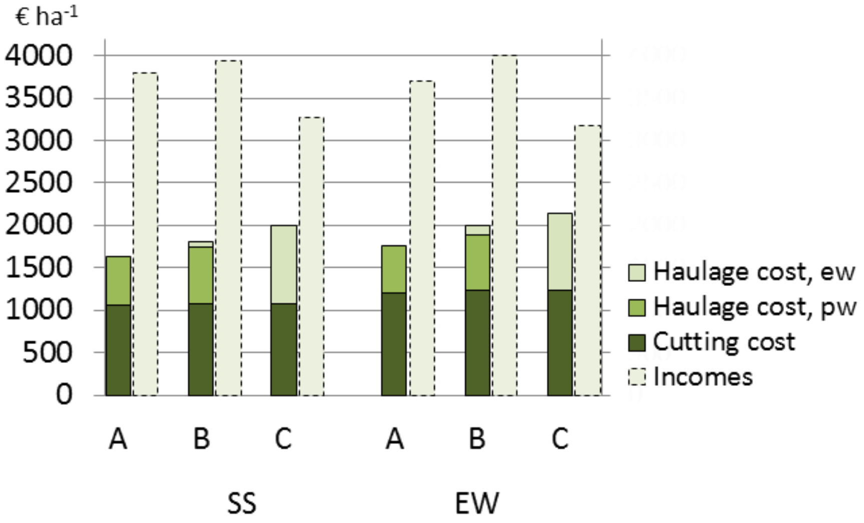

*Figure 7. Structure of incomes and costs in two example stands.*

There were two main reasons for the poor performance of whole-tree energy wood: lower price on roadside (21 € $m^{-3}$ vs. 30 € $m^{-3}$ for pulpwood) and higher forest haulage costs because of relatively lightweight loads. The harvesting costs per $m^3$ were actually the lowest in method C, but the total whole-tree harvesting costs per hectare were 10.4% and 7.3% higher than the costs of integrated harvesting in SS and EW stands, respectively. The load size used in haulage of whole-trees with branches was 6 $m^3$. In these two examples, harvesting method C would have reached the same level of profitability with other methods if the price of whole-tree energy wood had been ca. 27 € $m^{-3}$. Alternatively, harvesting costs of the method C should be about 50% lower with energy-wood price 21 € $m^{-3}$, before it would be competitive compared to pulpwood or integrated harvesting. This would be reached with load size of 8.5 and 9.6 $m^3$ in SS- and EW-stands, respectively. Nevertheless, the whole-tree method C is not competitive because of lower price of energy wood. If harvesting costs could be equalized, energy-wood price in method C should still be 4.0–4.5 € $m^{-3}$ higher, before it would reached the level of integrated or pulpwood regimes.

### 2.1.4 Discussion

The total area of birch-dominated stands on drained peatlands, ca. 0.5 million hectares, is a significant reserve of both pulpwood and energy wood. The structure, volume, and growth potential of the stands enable application of different harvesting methods and management regimes so that the best possible gain can be reached.

Among the three studied harvesting methods, the whole-tree method, where all aboveground tree biomass was collected for energy with up-to-date machinery, was the least profitable. Correspondingly, the most profitable method seemed to be integrated harvesting, where small stems (dbh 3.5–6.5 cm) and tops (d< 6.5 cm) of stems were collected for energy wood as lopped poles and larger stems for pulpwood. The share of lopped poles of total removal varied from 5% to 70%, decreasing with increasing thinning intensity and final-cutting age.

Both the total removal and the profitability of management varied considerably with the intensity of the first thinning (Table 9). The most profitable management regime was growing a dense downy birch stand without any kind of thinning. In case that one thinning was applied in young stands, light and moderate thinning intensities were more profitable than heavy or very light thinnings.

Short rotation length, 30 or 40 years, was economically inferior when compared to 55 years, according to both NPV and BLV results. This results from the high harvesting costs of small stems. More mature downy birch stands that had been managed with light precommercial thinning as sapling stands were more profitable when grown for 70 years, compared to final cutting at 55 years. The traditional first thinning of birch stands at the PW-stage was not profitable with interest rates less or equal to 3%, but because thinning had very small effect on NPV, in general, the decision between to thin or not to thin can be based on the other goals of forest management.

As expected, the more dense a birch stand was grown, the higher was the production of small diameter poles and branch biomass, whereas, unexpectedly, also the pulpwood removal was highest in unthinned stands. Thinnings combined with short rotation length were not profitable because of high harvesting costs of small stems. Quite a long growing period was competitive also for unthinned stands in spite of increasing natural mortality, because self-thinning was targeting the smallest stems that are the most expensive to cut. Precommercial thinning as well as energy-wood thinning seemed to be unnecessary and expensive treatments for pure downy birch stands on peatland. Thinning did not increase the value of the removal in final cutting. Moreover, it did not significantly decrease the harvesting costs per m$^3$ of the final cutting, because natural mortality had removed the smallest trees during the rotation, without any cost.

*Table 9. The effects of intensity and timing[1)] of thinning on the profitability of management, by rotation length (years): ++ means the best profitability and -- the lowest one.*

| Thinning intensity | SS | | | EW | | | PW |
|---|---|---|---|---|---|---|---|
| | 30 | 40 | 55 | 30 | 40 | 55 | 70 |
| No thinning | - | 0 | ++ | 0 | + | ++ | + |
| Very light | -- | -- | 0 | -- | -- | -- | + |
| Light | -- | - | + | -- | - | 0 | 0 |
| Normal | -- | - | + | -- | - | 0 | 0 |
| Heavy | -- | - | 0 | -- | -- | -- | - |

[1)] stand stage at the time of first treatment: sapling stand stage in group SS, energy-wood thinning stage in group EW, and pulpwood thinning stage in group PW.

On the other hand, also other goals than economic gain may be relevant reasons for applying thinnings, such as regeneration of spruce via undergrowth or the aspects of multiple use or landscape. On the most nutrient-rich sites with a high production potential, when the quality of the downy birch stands is high it may also be possible to produce veneer timber besides pulp and energy wood. In such cases, different kind of management regimes than those discussed in this study should most likely be applied.

In all studied rotation lengths the total removals were lower in SS- and PW-stands than in EW-stands whenever treatments (precommercial or commercial thinning) were applied. This was due to the precommercial thinning which does not result in a merchantable cutting removal, and the growth loss caused by early uncommercial thinning. This conclusion was proved in unthinned SS-stands, where the production of small diameter poles and branch biomass reached the same level as in EW-stands at the age of 55 years. The costs of late precommercial thinning or energy-wood thinning were very high in dense birch stands and therefore the NPV of thinned seedling stands (SS) were higher than those of older EW-stands, even if the rotation length was 55 years.

As to forest management regimes generally, the thinnings are more profitable (or at least less unprofitable) when higher interest rates are used. In the stands examined here, this was true only in tended downy birch stands at normal first thinning stage (PW), but the difference between thinned and unthinned stands was very small. Because precommercial thinning caused costs (SS stands) and energy-wood harvesting in EW stands also often caused net costs or the net income was very low without any subsidies, the effect of interest rate was the opposite in dense downy birch stands. The higher interest rate was used, the more profitable were the unthinned stands. Because of the low growth potential and low thinning response of downy birch, the compensation of the costs of precommercial thinning or early thinning takes place very slowly if at all. In addition, the yield of valuable timber is missing in practical scale because of the low quality and small size of the stems.

In all rotation lengths whole-tree harvesting was the least profitable, with the method and machinery as well as the prices and costs applied in this study. For improving the profitability of whole-tree harvesting to be competitive with other methods, the prerequisite 30% higher energy-wood price or almost 50% lower harvesting costs are too hard to meet in practice, but perhaps half of both changes may be realized in future. Then whole-tree harvesting for energy wood could be as profitable as integrated harvesting.

It may be possible to increase the productivity of final cutting in dense stands with small stems by developing new multi-tree cutting methods and machinery, but the productivity of forest haulage must rise as well. However, the small size of whole-tree loads used in this study can be an underestimate even for up-to-date skidders in final cutting of mature birch stands with a considerable amount of long stemwood logs. As a conclusion, we estimate that 15% higher price and 30% higher productivity in whole-tree harvesting in final cutting would be enough to make the whole-tree energy-wood harvesting competent in birch stands.

## 2.2 Pine-dominated stands on low-productive drained peatlands

Kojola, S., Salminen, H., Ihalainen, A., Lehtonen, M. & Laiho, R.

### 2.2.1 Introduction

In some drained peatlands, the initial drainage has not resulted in the desired improvement in wood production. Low productivity is often due to northern location or nutrient-poor site type. Sometimes low productivity is caused by a sparse growing stock, which, in turn, may be due to inadequate drainage, failed regeneration, or some abiotic damage. The quality of the stands also varies depending on the proportion of trees born before versus after the drainage, and on how well the first-mentioned trees have responded to the improved growing conditions following drainage.

Traditionally, forestry land has been divided in *forest land*, *poorly productive forest land*, and *unproductive land* according to wood production potential of the site (see table 3). According to the recently revised Forest Act (1085/2013), stand regeneration will not be required in the poorest drained peatland sites classified as *poorly productive forest land* or *unproductive land*. This means that such sites can be harvested without any subsequent costs. Among sites classified as *forest land*, however, there are also relatively low-productive stands, showing growth just somewhat over 1 $m^3ha^{-1}a^{-1}$, where stand management is unprofitable at least with present levels of prices and costs. These sites may be especially problematic for the forest-owners. Generally, management of low-productive sites, whether *forest land* or *poorly productive forest land*, calls for new guidelines focusing on profitability.

Most of the initial peatland drainage for forestry purposes took place within a relatively short time period in the 1960s and 1970s. Therefore, most of the drained peatland stands presently are thinning stands, where cutting removals consist of pulpwood and energy wood, and only a small proportion has reached the maturity for regeneration. The productivity of the second tree-generation after initial drainage in the low-productive sites is also difficult to predict. Thus, when the regeneration costs will be taken into consideration, it is obvious that based on their low profitability, the poorest areas should be left out of forestry use after harvesting of the first tree-generation for pulpwood or energy wood.

The exploitability of trees for pulpwood or energy wood depends on the profitability of the harvesting operation, which, in turn, varies considerably according to stand structure and size of the cutting area. The often heterogeneous stand structure, low stand volume, and low bearing capacity of the ground are typical challenges for harvesting in low-productivity sites, especially. Management focusing on energy-wood harvesting could overall be a potential alternative in low-productive sites for traditional management focusing on pulpwood and logs. Further, we know that there are sites well representing productive forest land, where the quality of pine is too low for sawlogs. Even there, it may be more profitable to harvest only pulpwood or energy wood, sometimes applying only final cutting. In the areas classified as *poorly productive forest lands,* the question will thus be: Is it profitable to harvest the existing tree stocks? In the sites classified as *forest land*, the task is, instead, to find the most profitable silvicultural management regimes.

The aims of the study were i) to identify the total area, regional distribution, and stand structures of low-productive drained peatland sites, ii) to examine the potential that these areas have for energy-wood production, iii) to specify profitable management regimes and optimal timings for the final cutting for both traditional timber harvesting and energy-wood harvesting, and further, iv) to identify stands, where forest management aiming at wood production will be unprofitable now and/or in the future.

We first identified the area and structure of low-productive stands on drained peatlands using Finnish National Forest Inventory (NFI) data and specific criteria targeting low productivity. Secondly, we simulated the long-term (100 years) development of a subset of the NFI-sample plots, representing the lower end of production potential in *forest land* according to several management regimes, and, based on the optimum solutions, compared the profitability of different management strategies.

The stands examined in this study represented the first tree-generation after the initial drainage, but also the profitability of regeneration and management of the next tree-generations is discussed. The stands were pure Scots pine (*Pinus sylvestris* L.) or pine-dominated stands on low-productive site types on drained peatlands.

### 2.2.2 Material and methods

#### *2.2.2.1 Low-productive drained peatland stands*

We picked up all such NFI-sample plots (NFI11, measured in 2009–2012) of the forestry land available for wood production (i.e., nature conservation areas excluded) that were classified as either *forest land*, *poorly productive forest land*, or *unproductive land* (see table 3), which met the set criteria of low productivity according to site type, temperature sum, and stand volumes (Table 10). The results were analyzed per five climatic regions (Table 2).

#### *2.2.2.2 Productivity and profitability of long-term management*

For the study of long-term (100 years) stand management we selected a subset of NFI-sample plots, simulated the development of these stands according to different management regimes with the Motti-simulator (Hynynen et al. 2005, 2014, Salminen et al. 2005), and used linear programming (Lappi and Lempinen 2013) to select the best regimes for each stand with set restrictions. The study proceeded with the following steps.

*Table 10. Criteria for low-productive drained peatlands from NFI11 sample plots. Site types, see Table 1.*

| | | Area according to temperature sum | Drained peatland forest site type | Stand volume |
|---|---|---|---|---|
| Land available for wood production, drained peatlands | Forest land | < 750 d.d. | All | Outside of the other criteria: advanced thinning stands and mature stands,<br>< 45 $m^3ha^{-1}$ |
| | | < 830 d.d. | VT1, DsT, ClT | |
| | | < 1000 d.d. | DsT, ClT | |
| | | > 1000 d.d. | ClT | |
| | Poorly productive forest land and unproductive land | All | All | |

**The study steps**

1. From NFI10 data (2004-2008), we selected ca. 4500 sample plots located on *forest land* and on *the land available for wood production,* and on three low or medium productive site types, Cladonia type (ClT, Table 1), dwarf-shrub type (DsT), and Vaccinium vitis-idaea type 1 (VT1). Of these, the poorest site type, ClT, is generally classified as *poorly productive forest land*, although some plots were also included into this data set of *forest land*. The DsT sites are generally relatively well stocked with stands that show good quality and growth sufficient even for saw timber production in Southern Finland, but their productivity decreases towards north. VT1 sites are generally productive, but individual stands may be low-productive due to insufficient stocking.

2. We grouped the selected data into five climatic areas: South, West, East, North, and Lapland (Table 2), and calculated regional distributions of site types based on the representativeness of each sample plot.

3. The present stage of the stands (according to the NFI-sample plot data) formed the input data for simulations. We simulated the development of each stand according to different management regimes until final cutting. Then the development of the next tree-generation was simulated until the total simulation time reached 100 years.

4. We considered four different main strategies defined by their emphasis on either timber (T) or energy wood (E) production and the choice of regeneration management. After the present tree-generation the sites were assumed to be artificially or naturally regenerated, and active silviculture continued **(strategies T1 and E1)** or they were left without treatments, i.e. left out of forestry use after the final

cuttings **(strategies T2 and E2)**. We assumed that even if the sites abandoned from forestry use would eventually be more or less forested, they would not be commercially utilized.

5. We defined several alternative management regimes and coded them to Motti-simulator (14–414 regimes depending on the site type). The harvesting methods included both energy-wood harvesting and conventional harvesting of pulpwood and sawlogs (= timber). Several alternatives for final-cutting criteria (mean diameter threshold) were generated within each management regime in order to facilitate enough space for linear programming (step 7).

6. We calculated the incomes and costs for every thinning and final cutting. We used average real road side values based on statistics, and unit costs of harvesting and silvicultural treatments (Table 12). We predicted the time consumption of each operation with the productivity models incorporated in the Motti-simulator (Hynynen et al. 2014), and calculated net present values (NPV) for profitability comparisons.

7. We compiled a set of optimal solutions (Table 11) for each climatic region using the linear programming package J (Lappi and Lempinen 2013). The aim was to select the combination of management regimes that maximizes the NPV with 2 and 3% interest rates (npv2max, npv3max) while, depending on the strategy in question, the amount and structure of cutting removals were more or less constrained.

8. The main results were drawn for management focusing on timber (T1, T2) and energy wood (E1, E2) (Table 11). Further, a theoretical upper limit of energy-wood yield was assessed by maximizing its unconstrained total accumulation (totEmax).

### Details of the simulations and calculations

The **management regimes** included alternatives for pulpwood harvesting, energy-wood harvesting and integrated energy- and pulpwood harvesting. Silvicultural and harvesting treatments included cleaning of sapling stand, precommercial thinning, first commercial thinning (timing defined by stand dominant height, intensity by stem number), later thinnings (according to general guidelines), ditch network maintenance (DNM), fertilization with wood ash, and final cutting (timing defined by stand mean diameter at breast height).

A major part of the **initial stands**, based on the NFI-sample plot data, represented the first tree-generation after initial drainage. Thus, the first treatments generally were commercial thinnings and DNM, and only seldom precommercial thinning. Some of the stands were recently regenerated, however, having a cleaning of sapling stand as the first treatment. The alternative management regimes defined for the simulations of the present stands included considerable variation in several respects (timing of cuttings, applying or not of DNM and fertilization), whereas the regimes for next tree-generation were more simple.

*Table 11. Optimization tasks.*

| Description | Aim at producing | Maximize | Constraints |
|---|---|---|---|
| Strategy 1: Active silviculture, regeneration after the final cutting[1] | Timber T1 | NPV[3] | Set an allowable range of decadal timber removals[4], limit decadal energy-wood removals close to minimum |
| | Energy wood E1 | | Set an allowable minimum of decadal energy-wood removals[5] |
| | Timber and energy wood UNCON1 | | None (an unconstrained optimum) |
| | Energy wood totEmax1 | The total removal of energy wood | None (a theoretical potential of energy-wood production) |
| Strategy 2: Active silviculture for the present generation, leaving out of forestry use after the final cutting[2] | Timber T2 | NPV[3] | Set an allowable range of decadal timber removals[4], limit decadal energy-wood removals close to minimum |
| | Energy wood E2 | | Set an allowable minimum of decadal energy-wood removals[5] |
| | Timber and energy wood UNCON2 | | None (an unconstrained optimum) |
| | Energy wood totEmax2 | The total removal of energy wood | None (a theoretical potential of energy-wood production) |

1) Silvicultural management will be actively continued in all stands (excluding CIT) by applying regeneration, fertilization, DNM etc.

2) After harvesting present tree-generation, all areas will be left out of forestry use.

3) Net present values, interest rates 2% (NPV2) or 3% (NPV3).

4) The lower limit is 80% of the mean decadal removals in UNCON and the upper limit is 80% of the mean decadal removals of the first 30 years in UNCON.

5) The lower limit is 80% of the mean decadal removals in totEmax.

**Harvesting removals** were cut according to generally used assortment rules. An average correction factor, based on NFI-data, was used to include a part of the sawlog volume as pulpwood because of inadequate quality of stems. Clearing before harvesting was considered unnecessary in these stands. Energy wood was collected as lopped poles both in integrated harvesting and in pure energy-wood harvesting. Lopped poles included the tops of harvested pulpwood stems and stems of the trees smaller than pulpwood size. The minimum diameter of trees harvested as energy wood was 4–6 cm, depending on the harvesting method.

**Cutting incomes** were calculated using long term mean values (real roadside prices) according to statistics from years 2000-2012 (Metinfo 2014). Statistics by harvesting methods are available only as stumpage prices. We multiplied the mean roadside prices by the relative stumpage prices of the different harvesting methods in order to estimate roadside price for each harvesting method. As a result, the prices were somewhat lower for first thinning removals and higher for final-cutting removals (Table 12).

**Costs** of silvicultural treatments and harvesting were defined by the time consumption models of the Motti-simulator and unit costs (long term mean values) from statistics (e.g. Koneyrittäjät 2014) (Table 12). Precommercial thinning was done with clearing saw and planting was done manually. Costs of planting and seeding as well as fertilization included the material cost. Both prices and costs were deflated by the cost-of-living index (Tilastokeskus 2013).

After having simulated alternative management regimes for each stand, they were congregated as a variable space for **linear programming.** In linear programming it is assumed that the goal(s) of the decision maker can be described as a linear programming optimization problem (Lappi 1992). For instance, a decision maker may want to maximize the net present value of future incomes, subject to constraints.

The critical points in the linear programming approach are the properties of the variable space and the formulation of the optimization task, and the results must be interpreted with respect to both of them. In our case, the variable space is the outcome of the alternative simulations of the development of each stand. The predictions are resulting from the management regimes and their options, and the financial performance of each prediction is affected by the predefined unit costs and unit prices. One important factor is the time-frame, i.e. the length of the predictions. In the optimization task, the constraints set the boundaries of the space of feasible solutions, and the objective function defines the variable to maximize (or minimize).

In this study, we chose to maximize the NPV, and used similarity of the annual cutting removals between all decadals as a constraint (Table 11). However, the first optimization task was carried out without any constraints. By this we could explore the underlying growth potential. The interest rates of 2% (NPV2) and 3% (NPV3) were used when discounting the future costs and incomes into NPVs. In practice, each linear programming task was solved twice using NPVs based on 2% and 3% as objectives (npv2max, npv3max). We also calculated the theoretical energy-wood potential (TotEmax) without constraints and maximizing the energy-wood removals.

Table 12. *Prices and costs.*

| Prices1) | | | | | |
|---|---|---|---|---|---|
| | | | Logs | Pulpwood | Energy wood |
| Pine | | € $m^{-3}$ | 58.77 | 30.38 | 27.34 |
| Spruce | | | 57.45 | 35.22 | 27.34 |
| Birch | | | - | 30.53 | 27.34 |
| **Harvesting costs2)** | | | | | |
| Cutting | Thinning | € $h^{-1}$ | | 71.50 | |
| | Final cutting | | | 68.20 | |
| Haulage | Thinning | € $h^{-1}$ | | 50.00 | |
| | Final cutting | | | 47.60 | |
| Planning costs 1.28, measuring costs 0.03, and other fixed costs 36.75 € $h^{-1}$ | | | | | |
| **Silvicultural costs3)** | | | | | |
| Plants | Pine | € / plant | | 0.369 | |
| | Spruce | | | 0.410 | |
| Planting | Pine | € / plant | | 0.203 | |
| | Spruce | | | 0.225 | |
| Seeding | | € $ha^{-1}$ | | 212.3 | |
| Soil preparation | Mounding | € $ha^{-1}$ | | 315.0 | |
| | Patching | | | 270.8 | |
| Cleaning of sapling stand | | € $h^{-1}$ | | 35.0 | |
| Precommercial thinning | | € $h^{-1}$ | | 35.0 | |
| Fertilization | | € $ha^{-1}$ | | 273.2 | |
| Ditch network maintenance | | € $ha^{-1}$ | | 185.9 | |

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1) Real roadside prices according to statistics from years 2000-2012 (Metinfo 2014).
2) Real unit costs, long term mean values by statistics (e.g. Koneyrittäjät 2014).
3) Real unit costs according to nominal costs by statistics from years 2000-2012 augmented with information delivered by private forest companies.
1-3) Deflated by cost-of-living index (Tilastokeskus 2013).

### 2.2.3 Results

#### *2.2.3.1 Low-productive drained peatland stands*

The total area of low-productive drained peatland stands (for criteria, see table 10), was estimated to be 0.84 million ha. This was almost 17% of the total area of peatlands drained for forestry. All areas of *forest land* and about three quarters of *poorly productive forest land* were "well-stocked" and considered as "Forest" according to the FRA-classification (FAO 2006). The rest of the *poorly productive forest land* was "low-stocked" being "Other wooded land" (FRA-OWL) or "Other land" (FRA-OL) (Table 13). Most of the class OL was treeless *unproductive land*.

On an areal basis, most of the low-productive drained peatlands were situated in the regions of North and Lapland (Fig. 8). The most common site type was DsT, the areal proportion of which, of the total area of low-productive drained peatlands, varied from 44% in the West to 73% in the North (Fig. 9).

*Table 13. Area of low-productive drained peatland stands according to NFI11 (2009-2012), based on criteria defined in table 10.*

| FRA-Classes[1)] | Area, 1000 ha | % | Land classes |
|---|---|---|---|
| FRA-Forest | 290 | 34 | Forest land |
| | 355 | 42 | Poorly productive forest land |
| FRA-OWL | 115 | 14 | |
| FRA-OL | 84 | 10 | Poorly productive forest land or unproductive land |
| All | 844 | 100 | |

[1)] FRA-classes: Forest, OWL = Other wooded land, OL = Other land

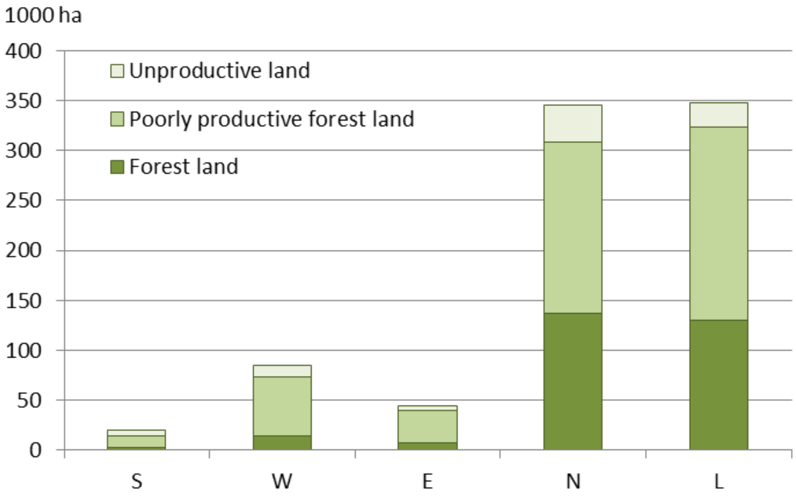

*Figure 8. Total area of low-productive drained peatlands by land classes and climatic regions. Regions: see Table 2.*

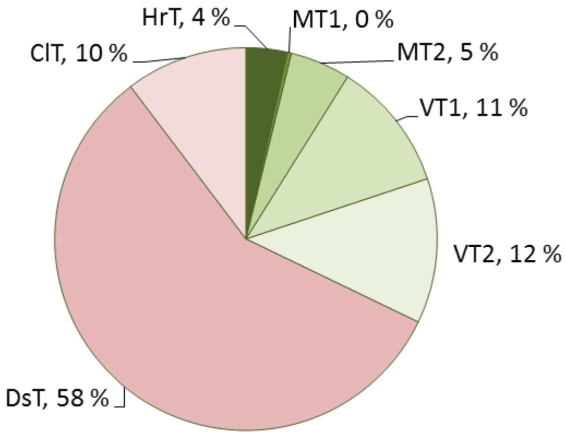

*Figure 9. Proportions of the different drained peatland forest site types of the total area of low-productive drained peatlands. Site types: see Table 1.*

*Table 14. Stand structure on low-productive stands on drained peatlands according to NFI11(2009-2012).*

| Land classes | | FRA-classes 1) | Area-weighted mean | | | Proportion of the area by volume classes, % | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | Diameter, cm | Height, m | Volume, m$^3$ha$^{-1}$ | < 15 m$^3$ha$^{-1}$ | 15–45 m$^3$ha$^{-1}$ | 45–75 m$^3$ha$^{-1}$ | > 75 m$^3$ha$^{-1}$ |
| Forest land | Young thinning stand | FRA-Forest | 12 | 9 | 49 | 2 | 45 | 41 | 12 |
| | Advanced thinning stand or mature stand | | 17 | 12 | 58 | 1 | 47 | 23 | 28 |
| Poorly productive forest land | | | 6 | 6 | 16 | 55 | 43 | 2 | 0 |
| | | FRA-OWL | 4 | 4 | 6 | 93 | 7 | 0 | 0 |
| Poorly productive forest land or Unproductive land | | FRA-OL | 1 | 0.5 | 1 | 99 | 1 | 0 | 0 |

1) FRA-classes: Forest, OWL = Other wooded land, OL = Other land

According to the NFI-data, the stand volume of the low-productive sites varied considerably. In most of the stands classified as *forest land*, the stand mean volume as average was between 15 and 75 m$^3$ha$^{-1}$, while for the “well-stocked” part of the *poorly productive forest land* (FRA-Forest), the volume was on average 16 m$^3$ha$^{-1}$ (range 5–83 m$^3$ha$^{-1}$) and for the “low-stocked” part (FRA-OWL) 6 m$^3$ha$^{-1}$ (range 0–30 m$^3$ha$^{-1}$), respectively. In almost all *poorly productive forest land* sites, the stand volume was less than 45 m$^3$ha$^{-1}$, and in the OWL-areas less than 15 m$^3$ha$^{-1}$ (Table 14).

The stand volumes indicate that the area, where harvesting (as clearcutting) could be economically viable would be the area of sites classified as *forest land* (ca. 290 000 ha), and about a quarter of the area of the “well-stocked” sites (FRA-Forest) on *poorly productive forest land* (ca. 88 000 ha). The largest stand volumes were generally found in DsT-type sites.

### *2.2.3.2 Productivity and profitability of long-term management*

In the previous section, general estimates were shown of the area and characteristics of drained peatland stands classified as low-productive according to site type, temperature sum and, with certain restrictions and concerning site types with a higher production potential only, stand stocking. The following results, in turn, are from an optimization study that included all stands classified as *forest land* and representing the three poorest site types, irrespective of their current stand volume. Thus, the areal estimates (per site types per region) differ from those presented in the previous section.

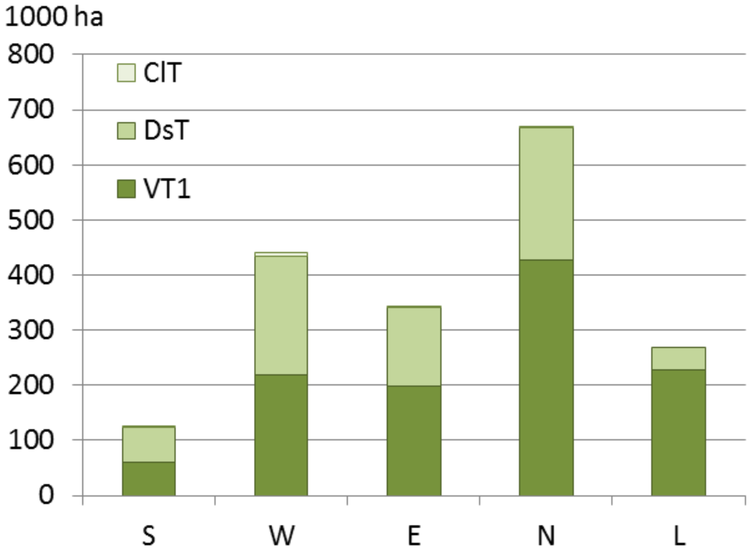

*Figure 10. Total area of the three drained peatland site types, included in the optimization study, by climatic regions. Site types: see Table 1, regions: see Table 2.*

### Site types and stands

The total area examined was ca. 1.8 million hectares. Most of the area was classified as VT1 (Fig. 10). Only 0.6% of the sites represented ClT classified as *forest land*, having minimal effect on the results. About 38% of the total area was classified as DsT. In the Lapland region, the proportion of DsT was smaller (15%) than in the other regions (Fig. 10).

At the onset of the simulations the distribution of stand development classes was relatively similar in the three southern regions: about half of the stands were at the stage of young thinning stands and one third were advanced thinning stands (Table 15). In the two northern regions the stands were younger, three quarters being young thinning stands. The area of stands classified as mature for regeneration was 5–10% and 1–2%, in the southern and northern regions, respectively (Table 15).

The tree species composition (% of stand volume) was quite similar in all regions: On both ClT and DsT, 97% was pine and 3% broadleaves trees, respectively, while on VT1 82% was pine, 6% spruce, and 12% broadleaves, respectively (data not shown).

Stand mean volumes generally decreased from south to north (Fig. 11). In the South region the differences between site types were at their largest, the mean volume increasing from 30 $m^3ha^{-1}$ in ClT to 90 $m^3ha^{-1}$ in DsT and 140 $m^3ha^{-1}$ in VT1(Fig. 11).

*Table 15. Distribution of stand development classes at the onset of the simulations, % of the total area of the three drained peatland site types studied.*

| Region | Temporarily unstocked regeneration area | Young seedling stand | Young sapling stand | Young thinning stand | Advanced thinning stand | Mature stand | Seed tree stand |
|---|---|---|---|---|---|---|---|
| S | 1 | 2 | 6 | 44 | 38 | 9 | 0 |
| W | 0 | 1 | 8 | 49 | 35 | 7 | 0 |
| E | 1 | 2 | 4 | 58 | 30 | 5 | 0 |
| N | 1 | 2 | 9 | 72 | 14 | 2 | 0 |
| L | 0 | 1 | 20 | 76 | 2 | 1 | 0 |

## Outcomes of the optimization tasksT1, T2, E1 and E2

The unconstrained maximum of NPV (UNCON1, UNCON2) was an auxiliary variable that was used when defining the allowed range of decadal removals in T1 and T2. The constraints used reduced the mean NPV2 by 21–78% (Table 16). Limiting the range of decadal removals actually postponed the potential final cuttings to a later point of time, which reduced the present value of incomes. The unconstrained maxima of energy-wood recovery (totEmax1, totEmax2) were used when defining the minimum level of decadal energy-wood removals in E1 and E2.

The management regimes and optimization tasks based on the four main strategies resulted in four different outcomes: T1, T2, E1, and E2. T1 aimed at producing timber while roughly following the current silvicultural recommendations. Timber production was also targeted in T2 but no regeneration was assumed after final cutting. Energy-wood production was predicted similarly by two alternative procedures; with (E1) or without (E2) active regeneration practices.

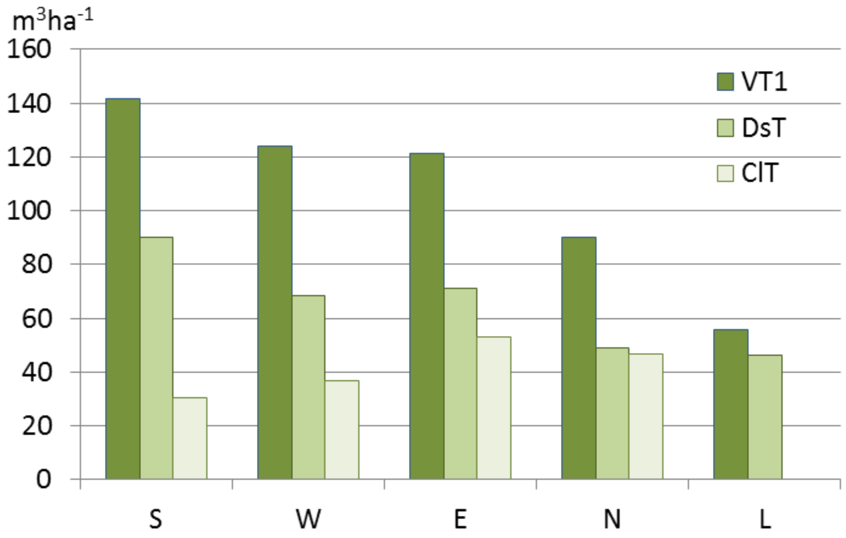

*Figure 11. Average stand volume at the onset of the simulations in the three drained peatland site types studied, by climatic region. Site types: see Table 1, regions: see Table 2.*

Table 16. The average net present value (NPV2, € ha$^{-1}$) of the unconstrained optimum (UNCON1 and UNCON2) and the relative NPV of T1, E1, T2 and T3.

| Region | NPV2 | | | | | |
|---|---|---|---|---|---|---|
| | UNCON1 | T1 | E1 | UNCON2 | T2 | E2 |
| S | 3197 | -24% | -27% | 3542 | -21% | -22% |
| W | 2273 | -46% | -34% | 2521 | -40% | -40% |
| E | 2400 | -46% | -34% | 2687 | -45% | -41% |
| N | 1286 | -76% | -28% | 1493 | -78% | -30% |
| L | 572 | -60% | -33% | 746 | -62% | -31% |

Stand mean diameter was used as the criterion for final cutting and maximization of NPVs favoured criteria that kept rotation times short without sacrificing the production of either timber or energy wood (Table 17). The value increment when shifting from pulpwood to sawlog-sized timber on one hand, and the net incomes from the final cutting on the other hand affected the selection of the final-cutting stage, when aiming at timber production. Timber assortment pricing does not play a role in energy-wood production and energy-wood recovery was also allowed to use shorter rotation times (lower diameter criteria) which influenced the results. The total removals of E1 and E2 were higher than those of T1 or T2 in all the regions except South. As a result, the standing stock remained at a lower level in E1 and E2 compared to T1 and T2 (Appendix 1). The price difference between pulpwood and energy wood was 10%, and the decadal removals of energy wood were limited only from above compared to timber removals that had both upper and lower limits. All these factors more or less favoured energy-wood production.

The diameter growth of trees is slow in low-productive peatlands, especially in Northern Finland. Accordingly, the share of areas that were predicted to be final cut in timber production alternatives T1 and T2 during the 100-year period was clearly higher in South, West and East than in North and Lapland. When aiming at energy-wood production, almost all the area was final cut at least once within the time frame of 100 years in all regions (Table 18).

*Table 17. Average stand mean diameter (cm) at the final cutting, according to the solved linear programming tasks based on strategies T1, T2, E1, and E2 by climatic regions.*

| Region | Strategy | | | |
|---|---|---|---|---|
| | T1 | T2 | E1 | E2 |
| S | 24.1 | 22.9 | 19.9 | 20.8 |
| W | 23.8 | 22.7 | 18.7 | 19.7 |
| E | 22.8 | 23.1 | 18.6 | 19.9 |
| N | 21.1 | 21.3 | 17.2 | 17.3 |
| L | 17.7 | 16.7 | 15.0 | 15.0 |

*Table 18. Share of area (%) that was final cut at least once during the 100-year simulation period according to strategies T1, T2, E1, and E2 by climatic regions.*

| Region | Strategy | | | |
|---|---|---|---|---|
| | T1 | T2 | E1 | E2 |
| S | 94 | 95 | 99 | 99 |
| W | 62 | 66 | 99 | 100 |
| E | 67 | 68 | 99 | 99 |
| N | 22 | 23 | 96 | 96 |
| L | 17 | 23 | 93 | 96 |

### Theoretical energy wood maximum (TotEmax)

When searching for a theoretical energy-wood maximum, the volume of harvesting removal from the whole 100-year simulation period varied from 30 to 130 million $m^3$ depending on region (Fig. 12). Mean annual removals were largest in the South (2.9 $m^3ha^{-1}a^{-1}$) and smallest in Lapland (1.4 $m^3ha^{-1}a^{-1}$) (Fig. 13). Differences between strategies 1 and 2 were small: mean annual removals of strategy 2 were about 10% lower than those of strategy 1 in the three southern regions, and almost equal in the two northern regions (Fig. 13). All economic viewpoints were neglected in the optimization when aiming solely at the theoretical energy-wood maximum. As a result, the economic performance of totEmax was low.

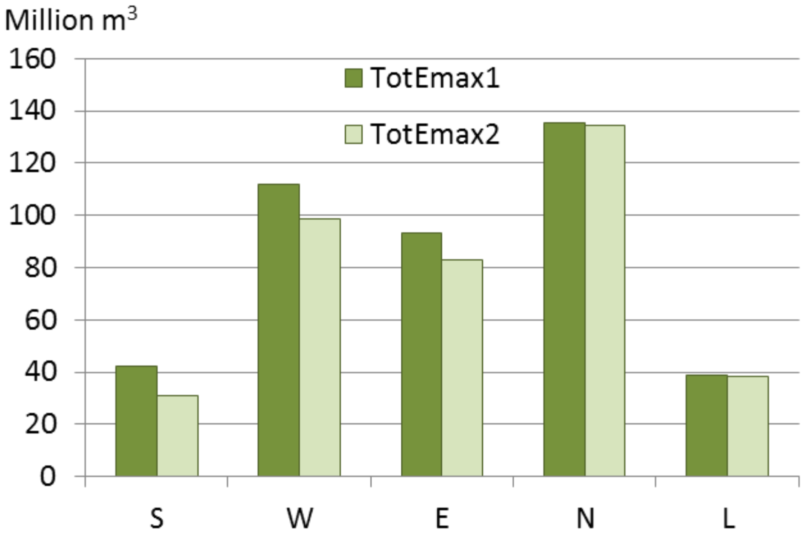

*Figure 12. Total removals of theoretical energy-wood maximum (100-year simulation, million $m^3$) in strategies 1 (TotEmax1) and 2 (TotEmax2), by climatic region.*

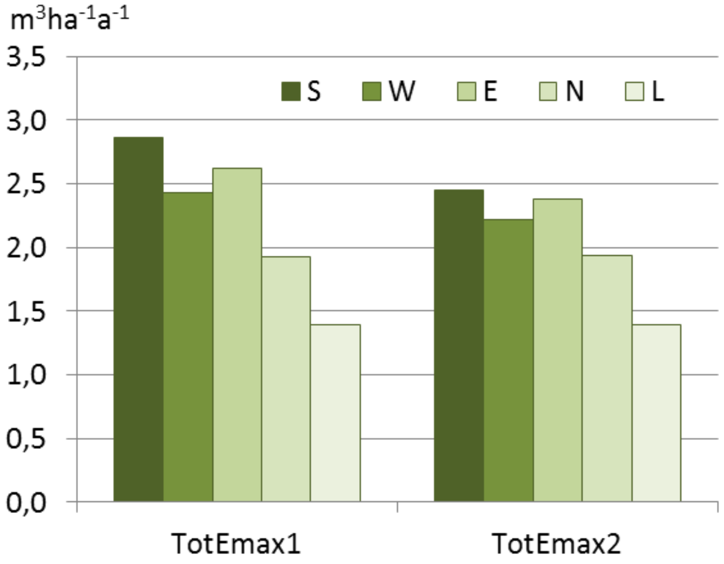

*Figure 13. Mean annual removals of the theoretical energy-wood maximum (annual means during 100 years, $m^3ha^{-1}a^{-1}$) in strategies 1 (TotEmax1) and 2 (TotEmax2), by climatic region.*

### Harvesting of pulpwood or energy wood (T1 vs. E1)

When comparing traditional management focusing on timber production (T1) and management focusing on energy-wood harvesting (E1) with 2% interest rate, T1 was more profitable (npv2max, NPV2) than E1 in the South region only. Energy-wood management was superior in all the other regions (Fig. 14). In the optimum solution with the higher interest rate (npv3max, NPV3), energy-wood management was competitive also in the South, whereas the balance tipped in favor of timber management in Lapland (Fig. 14).

The differences in profitability were partially due to the removals, energy-wood removal being at the same level in South and larger in the other regions when compared to removals in timber harvesting (Fig. 15). In addition, both the minimum and maximum decadal removals were controlled in T1 while only the minimum level was set in E1. Due to this, cuttings of the first decade were more pronounced in E1 as compared to the removals in T1 that were more even throughout the whole time frame. The other, but lesser, reason was that the total volume of silvicultural treatments was smaller and total cost was lower in the management focusing on energy-wood harvesting (Fig. 16).

Following from the largest total areas of drained peatland in North and West, the total harvesting removals were also at their largest in North (energy wood) and West (pulpwood or energy wood) (Fig. 15). The mean annual removals, on the contrary, followed rather the initial development classes and wood production potential that are more affected by climatic conditions, and generally decreased from south to north (Fig. 15).

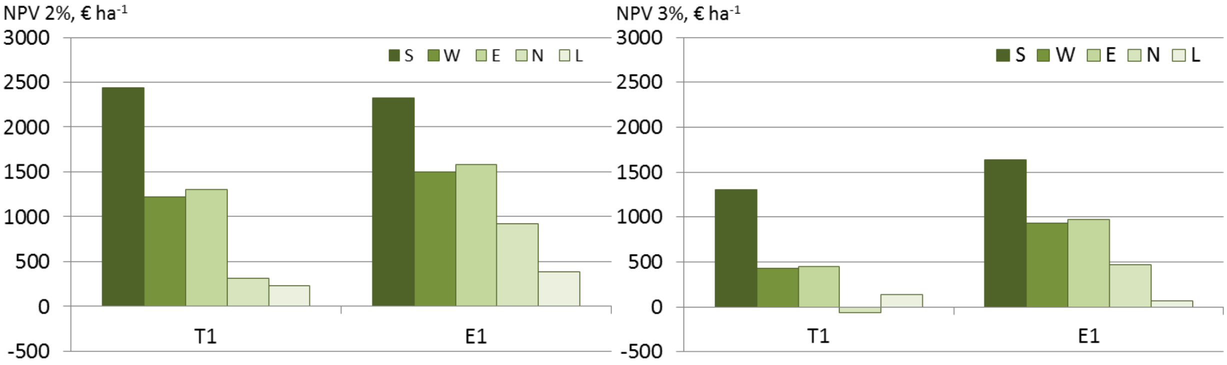

*Figure 14. Net present values (NPV2 and NPV3) from the optimum solutions npv2max and npv3max, when management was focused on timber (T1) or energy wood (E1).*

The largest differences between T1 and E1 were found in the North region. The energy-wood removals were 150% larger (Fig. 15), and resulted in fivefold NPV (Fig. 14) when compared to management for timber. In Lapland, energy-wood removal was fourfold when compared to timber removal, but the NPV was only about 1.5 times that of timber production (Fig. 14). That was mainly due to the different structure of the stands in North and South. In general, the stands in both the northern regions (N, L) were younger according to the time from the initial drainage, and their stand volumes lower than those in the three southern regions (S, W, E). Further, the final-cutting criteria, based on stand mean diameter, differed in energy wood and timber production strategies. In E1, the criteria were in a range that could be reached during the 100-year simulation time also in the northern regions, whereas in T1, final cutting was applied on only about 20% of the area in North and Lapland, on 60–70% of the area in East and West, and on 95% of the area in South.

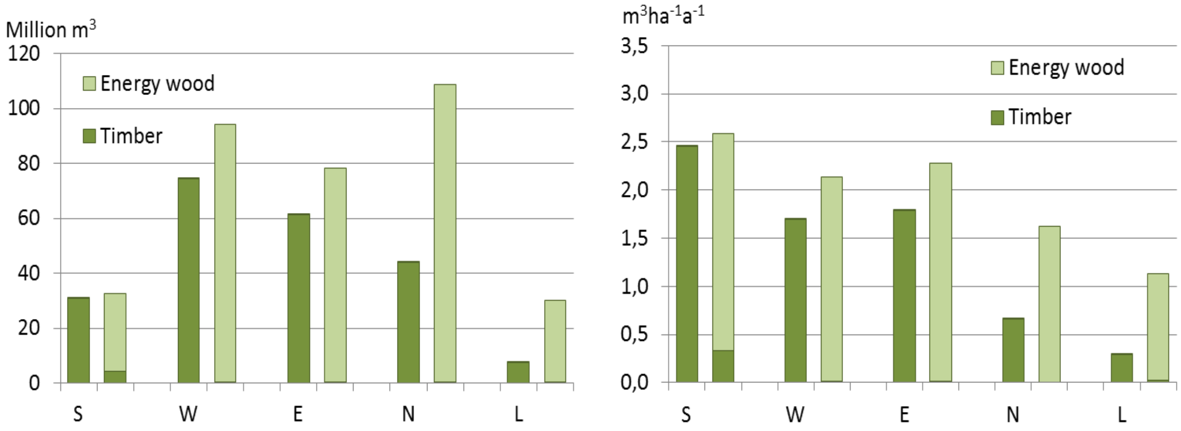

*Figure 15. Total removals (100 years, million m$^3$) and mean annual removals (during 100 years, m$^3$ha$^{-1}$a$^{-1}$), when management was focused on timber (T1) or energy wood (E1), based on optimization task npv2max (see Table 11).*

### Regeneration or leaving out of forestry use (T1 vs. T2, E1 vs. E2)

According to the results of optimum solution npv2max, abandoning of most of the areas from forestry use after final cutting of the first tree generation increased the profitability calculated for the 100-year period (Fig. 17). With NPV2, E2 was 0.3–36% higher than E1, and T2 was 8–24% higher than T1, respectively.

When undiscounted results were considered, the costs of silvicultural treatments were clearly lower in strategy 2 than in strategy 1 (Fig. 16), mainly due to the lack of treatments needed during and after final cutting. Especially, in management focusing on energy wood (E2), the volume of silvicultural treatments was low. Both the incomes and costs of E2 were slightly smaller than those of E1 (Fig. 16). The incomes of T2 were slightly smaller than those of T1 in South and West, being at the same level in the other regions (Fig. 16). The costs of T2 were on average 20% lower than those of T1.

Increasing interest rate decreased NPV in euros, but the relative differences between strategies 1 and 2 did not change considerably (Fig. 17). However, there were small changes in the ranking between T1, T2, E1 and E2: NPV2 of E2 were more or less higher (0.5–36%) than those of E1 in all regions, likewise NPV2 of T2 were higher than those of T1 (7–24%) (Fig. 17). In the optimum solution npv2max, profitability by NPV3 of E2 was slightly better than that of E1 (0.5–3%) in West and East, and lower in the other regions (22–180%), likewise NPV3 of T2 was higher than that of T1 in all regions (28–72%) (Fig. 17).

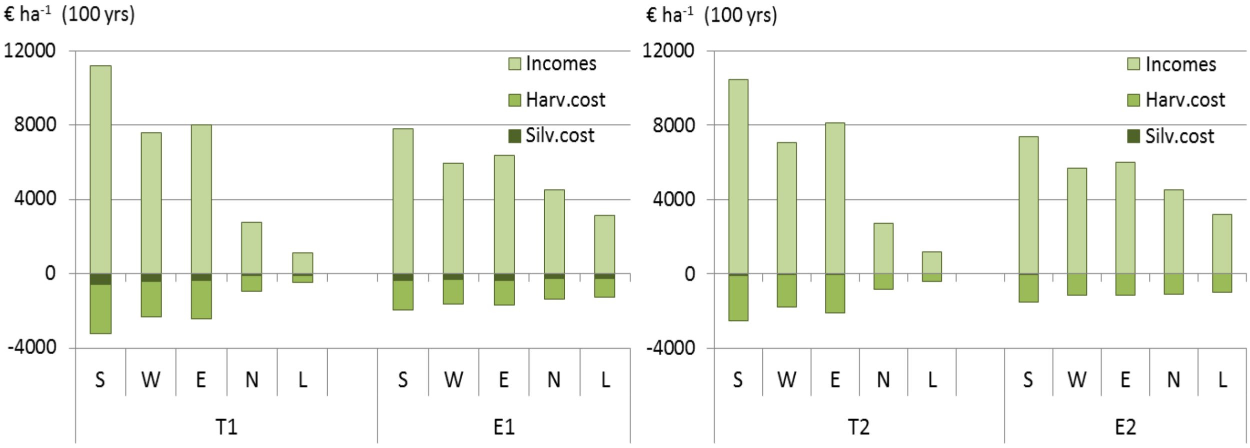

*Figure 16. The structure of the undiscounted incomes and costs (NPV0) in the optimum solutions for the different strategies T1, T2, E1, and E2.*

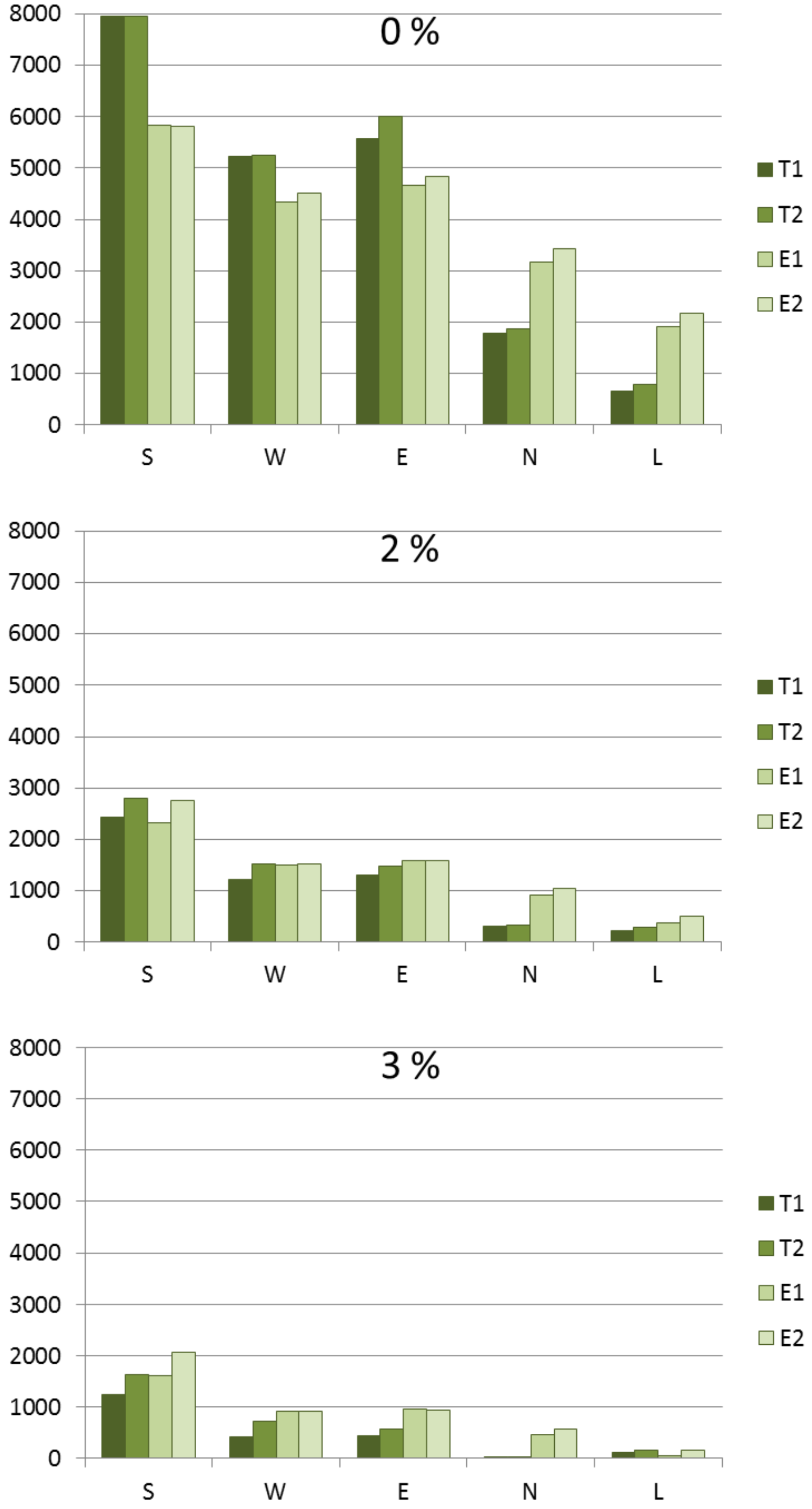

*Figure 17. Net present values (NPV0, 2%, 3%) of the optimum solution npv2max for the different management strategies T1, T2, E1, and E2.*

### Silvicultural treatments and cuttings in different optimum solutions (T1, T2, E1, E2)

Silvicultural treatments were applied most extensively in T1 (strategy 1, management focused on timber). The proportion of the area that was first regenerated and later in need of cleaning of sapling stand and/or precommercial thinning was at its largest in South, over 60% of the total area (Appendix 2, Table A1). In Lapland, the proportion of cleaning of sapling stand was at its smallest, 11% of the total area, and the proportion of precommercial thinning was as low as 7% of the total area. In the energy-wood regimes E1 and E2, the area of silvicultural treatments was small. Only DNM was applied more commonly in E1 (Appendix 2, Table A1).

In Lapland DNM was not applied. The proportion of DNM of the total studied area in T1 was 17%, 14%, 10% and 1% in South, West, East, and North, respectively. In timber management, DNM was applied almost equally in VT1 and DsT sites in South and West, whereas in East and North, more than 70% of the DNM was applied in VT1. In energy-wood management DNM was applied mainly in VT1.

In timber management, fertilization was applied almost equally in VT1 and in DsT sites in South and West. In East, fertilization was used more in DsT sites and in North more in VT1 sites. In energy-wood management, some DsT were fertilized in South, but only VT1 in the other regions. In Lapland and North fertilization was rarely applied.

Thinnings were applied most extensively in T1 (Appendix 2, Table A2). In the three southern regions first thinnings were applied in 45–55% of the total area, and in the two northern regions in 20–25% of the total area. Other thinnings were applied in 55–65%, 35%, and 5% of the total area, in the three southern regions, North, and Lapland, respectively.

In South, the area of final cuttings did not depend on the strategy (Appendix 2, Table A2). In West and East the final-cutting areas of strategies T2 and E2 were ca. 1.5 times of the respective area in T1, and in E1 almost double (180%) that of T1 (Appendix 2, Table A2). In the northern regions, the final-cutting area was small in the timber management T1, 22% and 17% of the total study area in North and Lapland, respectively. Correspondingly, in the energy-wood management E1 final cuttings were applied in multifold when compared to T1, the area being 99% and 93% of the total study area in North and Lapland, respectively. The diameter thresholds for final cutting were lower in the energy-wood alternatives than in timber production.

In strategy 1, all final-cutting areas were regenerated, whereas in strategy 2 the areas were not actively regenerated after final cutting. Depending on the region, the proportion of area regenerated after final cutting (T1, E1) varied between 0–1% and 16–114% of the total area, in artificial and natural regeneration, respectively. Thus, almost all areas were regenerated naturally and some areas were regenerated twice during the predicted 100-year period.

### 2.2.4 Discussion

In this study, low-productive drained peatlands were examined using two different approaches. First, the estimates of low-productive areas were produced by beforehand-set criteria of temperature sum and site types. This NFI11 sample consisted of drained peatlands classified as *forest land, poorly productive forest land*, or *unproductive land*, resulting in a total area of 0.84 million hectares. Two thirds of the area was classified as *poorly productive forest land* or *unproductive land*, where the current Forest Act (as of January 1, 2014) allows final cuttings without regeneration. The proportion of such sites was largest in the regions North and Lapland. In almost all this area, the stand volume remained below 45 $m^3ha^{-1}$, in most cases below 15 $m^3ha^{-1}$; thus, only a minor part of these sites can be reasonably good for harvesting, even though clearcutting without regeneration can be used.

Secondly, stands on *forest land* and representing the three drained peatlands site types at the lower end of the productivity gradient, based on NFI10-data, were examined by predicting their development for the next 100 years and comparing the profitability based on the optimum solutions of different forest management strategies (i.e. timber or energy-wood management, regeneration (strategy 1) or abandoning from forestry use (strategy 2) after final cutting). This study concerned ca. 1.8 million hectares. It is worth of noticing that these two areal estimates did not represent exactly the same population, the latter including also relatively highly-stocked stands.

In the optimization study, the few ClT stands (0.6% of the study area) had a minor role. The stands on DsT (38%) and on VT1 (61%) were mostly well stocked, having average stand volumes of 45–90 $m^3ha^{-1}$ and 55–140 $m^3ha^{-1}$, respectively. Nuutinen et al. (2000, Table 13) estimated that the maximum sustainable removal from peatland forests of Finland in 1996–2026 is 12–13 million $m^3a^{-1}$. Based on that, the harvesting potential of the area representing the three site types studied, about 2–3 million $m^3a^{-1}$, is considerable. However, the differences between single stands as well as between regions are substantial.

The stands were younger judged by development classes in the northern areas, and more mature towards south, which greatly affected stand volume and cutting potential during the studied period. In addition to development class distribution, the tree growth, being slower in north, led to the situation where the treatments applied at different time points and in different management regimes, varied considerably between regions. For example, a clearly smaller proportion of total area was thinned or final cut in the two northern regions than in the three southern regions during the 100-year simulation period. Due to the small total area of thinnings in the northern regions, also the areas of DNM were small, because in the simulations they were allowed only together with thinning or regeneration.

When the optimization task was, without any constrains, to find the theoretical potential of energy-wood production, TotEmax, for the next 100 years, the resulting removals were from 30 to 130 million $m^3$ depending on the region. In the three southern regions, total removals were somewhat higher when forest management was continued after the final cutting of present stands, whereas in the northern areas both strategies resulted in almost the same total removals. The differences between regions were obviously due to the different climatic conditions but also to the different initial growing stocks and stand structures. Comparison of the theoretical energy-wood potential, TotEmax, to the total energy-wood removals of E1 and E2, where NPV was maximized within specific constrains, indicated that roughly 70–90% of the theoretical potential may be possible to harvest.

When the optimization task was to find the best management focusing on timber production or, correspondingly, the best management focusing on energy-wood production, the minimum and maximum decadal removals were used as constraints. According to these results, the total energy-wood removals were larger than timber removals in all regions except South. Thus, the growth potential of the sites was, in terms of NPV, in better use in energy-wood regimes. However, in South, the traditional timber management is a competitive alternative, when judged by removals and NPV2. Management focusing on energy-wood harvesting was more profitable towards north, and also in South with a higher interest rate than 2%.

The differences between timber and energy-wood regimes were largest in the northern areas. Especially in the North region the energy-wood removals, and likewise the profitability of management for energy wood, were remarkably high, when compared to timber management. The profitability of management for timber production in North was depressed because only a part of the stands reached the maturity for final cutting during the 100-year period that was the time frame of this study. Thus, the final-cutting incomes were realized very late or not at all. That was, again, due to the relatively young, and slow-growing, initial stands, where the trees reached the size of pulpwood logs and sawlogs late. The mean stand diameter used as final-cutting criterion for energy-wood stems was clearly lower, allowing an earlier final cutting.

The comparison between energy wood and timber management is strongly conditional to prices and costs used in the calculations. Here the price of energy wood was relatively high, close to the price of pulpwood, which means that the benefits of the energy-wood management may seem unrealistically positive. The price of energy wood used here can be considered as a subsidized price. When assuming a lower energy-wood price (e.g., 70% of pulpwood price, ca. 21 €$m^{-3}$, roughly corresponding the level indicated by statistics, Metinfo 2015) and assuming the cutting removals and timings according to the present optimum solution, the profitability of timber management would be more clearly more profitable than energy-wood management in South, and slightly better in West and East. In North and Lapland, however, energy-wood management would still be more profitable, but the gain would be lower than with the prices applied in our calculations.

According to the optimal solutions, the differences between the two strategies concerning the future tree-generations (1 regeneration or 2 abandoning from forestry use), indicated that abandoning from forestry use after final cutting of the present tree-generation would generally be a good solution, on condition that the time-frame is no more than 100 years and the interest rate is at least 2%. This was even though many of the stands included in the study were not low-productive enough to fulfill the legal criterion allowing final cutting without the obligation to regenerate. Continuing timber management to the next tree-generation was profitable in the three southern regions with 0%, but in none of the regions with NPV2 and 3%. On the other hand, it was profitable to continue energy-wood management in the three southern regions, and, correspondingly, to use only the present stands in the northern regions. The profitability of abandoning from forestry use after final cutting in most cases was partly due to the used time-frame. The net incomes from the first thinning were not necessarily enough to pay back the regeneration costs, and the following thinnings were not scheduled within the period of consideration. It all comes back to the interest rate applied and time-frame selected. From another viewpoint, active silviculture could still be an option if regeneration costs could be clearly reduced. In peatland forests, that means natural regeneration and cutting the costs of soil preparation and DNM.

When making the final conclusions, it is worth of noticing that the optimum solutions are presenting the potential (achieved with the methods selected as best), not the realization. The calculations are not direct predictions of the development of the selected peatland forests, but rather examples of some possible futures. When interpreting the results, the following points should be borne in mind: i) what are the key properties of the initial stand data, ii) what kind of management regimes were applied, iii) what unit prices and unit costs were used, iv) what was the aim of the optimization task, v) what interest rate was used, and vi) what was the time-frame of the study. Also, the conclusion concerning the non-profitability of continuing management in the northern regions was drawn in conditions that in many cases even the first rotation could not be finished during the 100-year simulation period.

The areal estimates are based on NFI sample plots, and because of that, the classification of the site types is conditional to NFI sampling and its accuracy. Likewise, the development stage and characteristics of the present stands are based on the NFI sample plots, thus mirroring the time of inventory.

Predictions of the stand development are prone to the performance of the actual growth models. Low productive sites are in the marginal of the original modelling data and there are only few second-generation stands in the data (Hökkä 1997, Hökkä et al. 1997). Therefore, the estimates of the yield of the first-generation stands should be at a correct level or slight overestimates at the most, but the predictions of the second tree-generation include a risk of underestimation.

The profitability of regeneration as well as the profitability of harvesting operations is most questionable just in the poorest site types of drained peatlands. Regeneration is often less profitable in drained peatlands than in forests on mineral soil sites, due to the effective methods needed for soil preparation and the special needs to maintain proper drainage, not forgetting water protection solutions. However, in many sites, the sparse and low-quality stands of the first tree-generation may be replaced by fully stocked, even-aged stands, which will most likely reach better levels of growth and yield.

In the three site types studied here, the costs of harvesting operations often increase because of low stocking and small average size of the harvested trees. The soft ground causes problems for heavy machines thus forcing to schedule cutting operations mostly on the time when the ground is frozen. When abandoning the areas from forestry use, many areas may be clearcut in relatively small stand mean diameter. Then the harvesting techniques of clearcutting can be applied, but the small total removal and stem size are still restricting the machines used. Therefore, economically viable harvesting of the most low-stocked stands calls for a large area, short distances in haulage, and, preferably, combining the low-productive area with a larger cutting area or timber trade agreement. In this optimization study, the harvesting costs were produced by models according to stand volumes and stem sizes. Thus, the challenging circumstances were not separately considered. Therefore, in the most low-stocked stands, harvesting costs can be actually higher, and in some stands, when their size and location are taken into consideration, the execution of the harvesting unprofitable.

## 2.3 Energy-wood harvesting in low-productive drained peatland stands

Kiljunen, N. and Soikkeli, P.

Approximately 900 000 ha of peatland on state-owned land managed by Metsähallitus have been drained to improve the growing conditions of trees (Table 19). In addition, over 100 000 ha of wet or moist mineral soils have been drained. This area is excluding peatlands in protected areas that may also contain some drained area. The outcome of the drainage operations varies markedly. Most of the drained area has produced more or less according to the set targets. However, a considerable area of such low-productive peatland sites were also drained (Chapter 2.2), where the resulting forest growth has been inadequate, less than 1 $m^3ha^{-1}a^{-1}$. Drained peatland sites producing less than 1 $m^3ha^{-1}a^{-1}$ are classified as *poorly productive forest land*.

To estimate the share of *poorly productive forest land* in Metsähallitus peatlands, the area and classification of drained peatlands in Metsähallitus forests was extracted from Metsähallitus GIS data, and for comparison, from the Finnish national forest inventory (NFI) data (table 19). Protected areas were excluded also here.

The difference between the figures is on one hand based on the old stand compartment structure, where large compartments have been classified as *poorly productive forest land* although they contain also *forest land*. The stand data in Metsähallitus forest information system may also be markedly older compared to NFI, which may have an effect on the results. Differences can also be explained by different evaluation methods for forest growth used in Metsähallitus stand data and NFI. Further analyses should be focused on land that is used in actual forestry (Table 20). The rest of the drained peatland area (approx. 200 000 ha) on forestry land is excluded from forestry use by Metsähallitus because of very poor fertility or as important landscape ecological planning objects, or for instance, because of adjacent protection areas.

*Table 19. Drained peatland area in Metsähallitus forestry forests.*

| | Metsähallitus forest data (ha) | NFI 2009–2013 (ha) |
|---|---:|---:|
| Forest land | 568 000 | 702 000 |
| Poorly productive forest land | 266 500 | 171 800 |
| Unprofitable land | 44 500 | 31 200 |
| TOTAL | 879 000 | 905 000 |

*Table 20. Drained peatlands in actual forestry use at Metsähallitus.*

| | NFI 2009–2013 (ha) |
|---|---|
| Forest land | 649 000 |
| Poorly productive forest land | 36 300 |
| Unprofitable land | 1 600 |
| TOTAL | 687 900 |

The main role of Metsähallitus in the BEST R&D Programme was the contribution to the task 2.1.3. There Niemi et al. (2015) studied the possibilities to define the border between low-productive and productive forest land using airborne laser scanning. The pilot study was carried out in Haapajärvi western Finland.

The main result of Niemi et al. (2015) was that laser scanning can be used for recognition of low-productive area on drained peatland if a small number of additional reference plots are measured. The studied method can be utilized for redrawing stand compartment geometry in a GIS system and thus to separate *forest land* from less productive peatlands. The real low-productive land will be left out of operations while the areas producing more than 1 $m^3ha^{-1}a^{-1}$ will be treated as productive forest. However, Metsähallitus has created special forest management guidelines for areas producing 1–2 $m^3ha^{-1}a^{-1}$ over the rotation period with a constrained variety of silvicultural measures.

A technology review concerning potential harvesting technologies did not reveal any promising new machinery for effective harvesting of small-diameter trees. Thus, no harvesting experiments were carried out as planned at the beginning of the project. Instead, rough cost calculations were done for final cutting of low-productive peatland using multiple-tree harvesting with a harvester (Fig. 18 and 19). Production and cost models for multiple-tree harvesting were available mostly from Laitila et al. (2014) and complemented from other sources. The hourly cost used for harvester was 85 €$h^{-1}$ and for forwarder 65 €$h^{-1}$. The functions were originally for birch. Cost estimates for pine (Fig. 18) were calculated using a productivity factor 0.9 for harvesting, which was drawn from previous studies for similar-volume trees of these species.

The dependence of unit costs on mean stem volume ($dm^3$) seems to be quite, even unexpectedly, flat. Possible reasons are that i) the forwarding cost is treated as constant on certain harvesting yield irrespective of stem volumes, or ii) the study (Laitila et al. 2014) is related to final cutting as multiple-tree harvesting. However, the effect of harvesting yield per hectare on the costs is high.

Further growing of stands decreases harvesting cost on low-productive stands. Thus, there is no hurry with harvesting the low-productive peatland forest stands if the stand is not threatened by any damage. More exact economic analysis would be needed on the profitability of the remaining rotation period. In practice low-productive sites could be harvested in connection to nearby normal harvesting site.

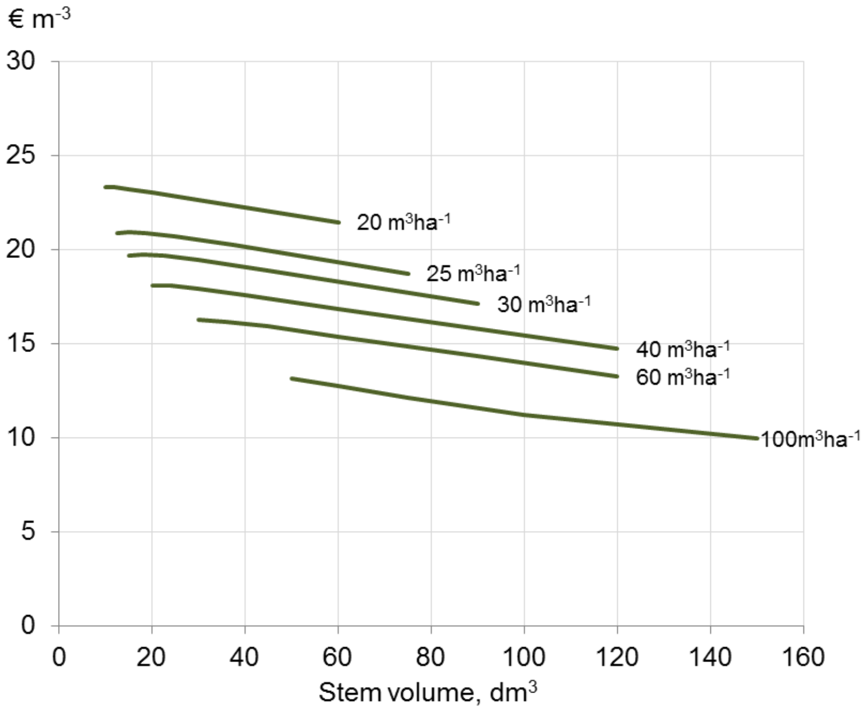

*Figure 18. Estimated harvesting costs for pulpwood in pine-dominated stands with different harvesting yields and average stem volumes.*

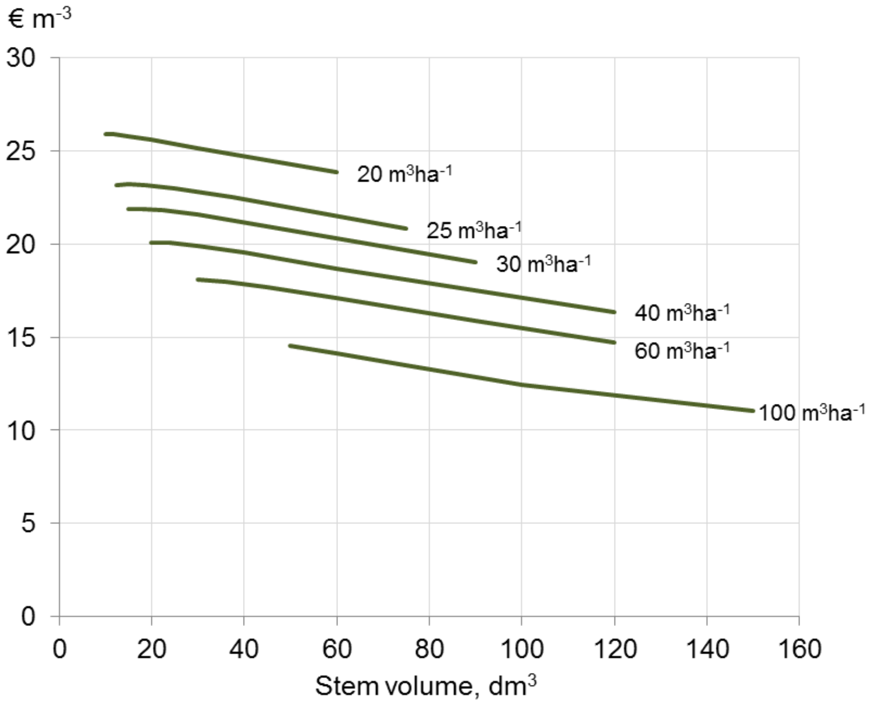

*Figure 19. Estimated harvesting costs for pulpwood in birch-dominated stands with different harvesting yields and average stem volumes.*

# 3 Conclusions

Birch-dominated stands on drained peatlands comprise a potential reserve of both pulpwood and energy wood. With present prices and costs, the best profitability was reached by integrated harvesting where both pulpwood and energy-wood poles were harvested. On the contrary, harvesting of whole-tree energy wood had clearly lower profitability when up-to-date machinery was used. To become competitive, the whole-tree energy-wood harvesting would need both 30% higher productivity in final cuttings and 15% higher price for energy wood. Precommercial thinning or early first thinning was unnecessary; it was most profitable to grow stands without treatments and to apply final cutting relatively late at the stand age of 55 years. However, if precommercial thinning or early light thinning was done, the final cutting should be delayed until stand age of 70 years. In that case, commercial thinning was not necessary but was possible without significant economic loss.

A moderate energy-wood potential exists also on low-productive drained peatland sites, but the exploitation of this wood may often be expensive. Because smaller stems can be used, management focusing on production of energy wood could often substitute management for timber, especially when the difference between pulpwood and energy-wood prices is small. This was evident in the results from northern Finland, especially, where the stands were at an earlier stage of development and growing slower than in the south: energy-wood recovery consistently outperformed timber production in terms of NPV. However, timber production can be a viable option in southern Finland. Long-term forest management on low-productive drained peatlands gives good financial results only in southern Finland where their total area is small. In general, the expected revenues from second generation peatland forests gets the smaller the more northern sites are examined. As in drained peatlands altogether, the variation between sites and stands is large, however, so the decisions on individual cases may differ from the general recommendations depending on the actual conditions of the stand.

A comparison between Metsähallitus forest stand data and NFI data provided information on harvesting potential of poorly productive peatland forests on state-owned land. A technology review did not reveal any promising new methodology for harvesting of poorly productive peatland forests. By means of cost calculation using existing production and cost models, a rough idea on harvesting costs could be created. Further growing of stands decreases harvesting cost on low-productive stands. Thus, there is no hurry with harvesting the low-productive peatland forest stands if the stand is not threatened by any damage. In practice low-productive sites could be harvested in connection to nearby normal harvesting site.

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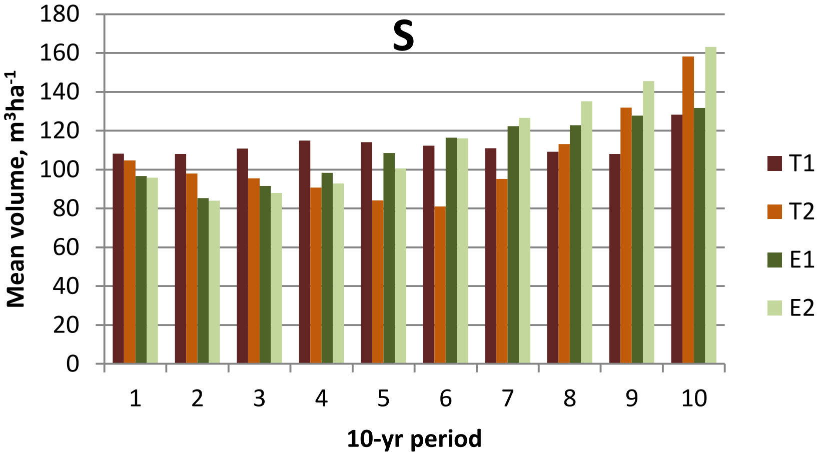
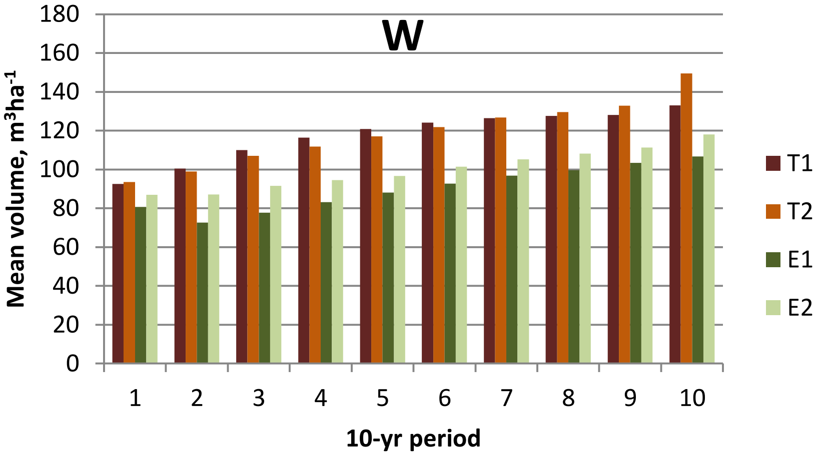
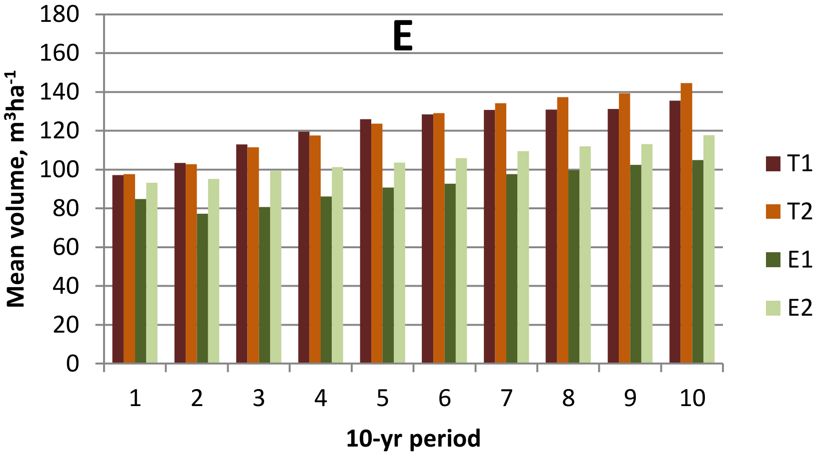
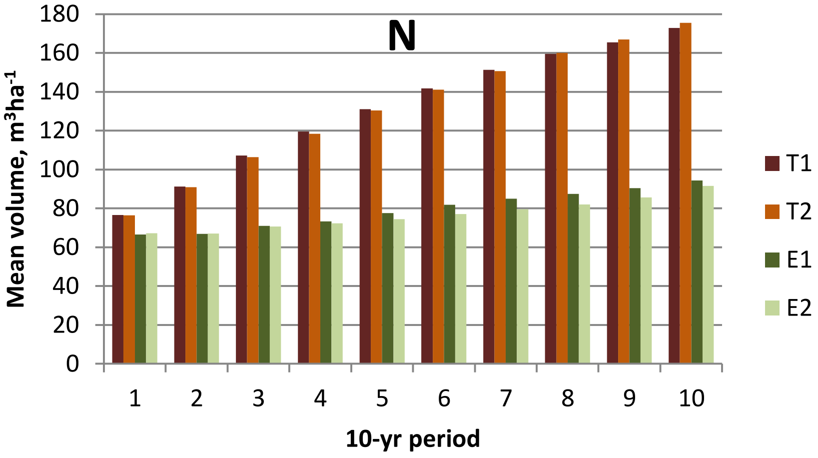
# Appendix 1.

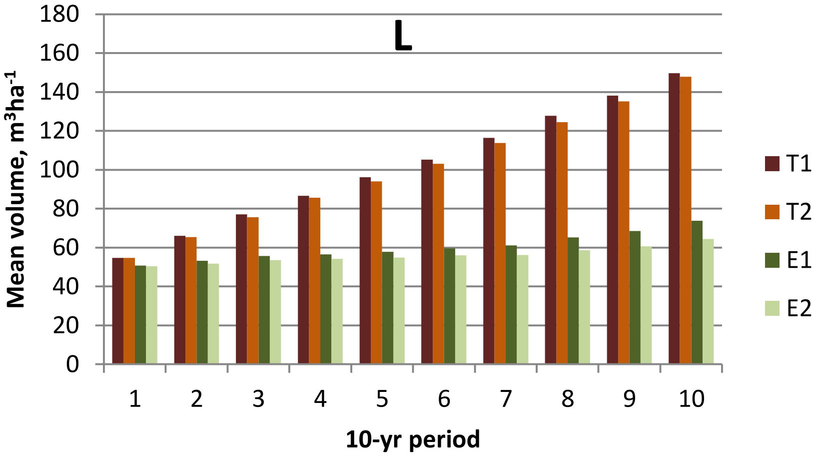
*Standing stock (predicted stand mean volume) in optimum solutions based on net present value (NPV2) according to strategies T1, T2, E1, and E2, in the five climatic regions S, W, E, N, and L. Regions, see Table 2.*








N
Mean volume, $m^3ha^{-1}$
0
20
40
60
80
100
120
140
160
180
1
2
3
4
5
6
7
8
9
10
10-yr period
T1
T2
E1
E2


L
Mean volume, $m^3ha^{-1}$
0
20
40
60
80
100
120
140
160
180
1
2
3
4
5
6
7
8
9
10
10-yr period
T1
T2
E1
E2

# Appendix 2.

*Table A1. Area of silvicultural treatments and their proportion of total area (= area of the three drained peatland sites studied in each climatic region). Management maximizing net present value (npv2max) and focusing on timber (T1, T2) or energy wood (E1, E2).*

| Treatment1) | Area, ha a$^{-1}$ | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | | | | W | | | | E | | | | N | | | | L | | | |
| | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 |
| CS | 802 | 35 | 69 | 48 | 2298 | 3 | 57 | 3 | 1654 | 6 | 41 | 0 | 987 | 8 | 68 | 12 | 286 | 0 | 89 | 0 |
| PT | 713 | 22 | 16 | 16 | 1387 | 36 | 17 | 17 | 1017 | 45 | 26 | 26 | 604 | 21 | 17 | 25 | 177 | 39 | 49 | 30 |
| F | 168 | 143 | 10 | 47 | 124 | 124 | 0 | 0 | 65 | 83 | 0 | 0 | 33 | 24 | 0 | 0 | 0 | 20 | 0 | 0 |
| DNM | 211 | 139 | 195 | 26 | 638 | 614 | 525 | 13 | 352 | 657 | 495 | 0 | 56 | 242 | 8 | 0 | 0 | 0 | 0 | 0 |
| Treatment1) | Proportion of the total studied area of region, % (in 100 yrs) | | | | | | | | | | | | | | | | | | | |
| | S | | | | W | | | | E | | | | N | | | | L | | | |
| | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 |
| CS | 63 | 3 | 5 | 4 | 52 | 0 | 1 | 0 | 48 | 0 | 1 | 0 | 15 | 0 | 1 | 0 | 11 | 0 | 3 | 0 |
| PT | 56 | 2 | 1 | 1 | 31 | 1 | 0 | 0 | 30 | 1 | 1 | 1 | 9 | 0 | 0 | 0 | 7 | 1 | 2 | 1 |
| F | 13 | 11 | 1 | 4 | 3 | 3 | 0 | 0 | 2 | 2 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 1 | 0 | 0 |
| DNM | 17 | 11 | 15 | 2 | 14 | 14 | 12 | 0 | 10 | 19 | 14 | 0 | 2 | 4 | 0 | 0 | 0 | 0 | 0 | 0 |

1) CS = Cleaning of sapling stand, PT = precommercial thinning, F = fertilization, DNM = ditch network maintenance

# Appendix 2.

*Table A2. Area and relative area (compared to T1) of cuttings in drained peatland sites representing the three site types at the lower end of the wood production potential, by climatic regions. Management maximizing net present value (npv2max) and focusing on timber (T1, T2) or energy wood (E1, E2).*

| | Area, ha a$^{-1}$ | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | S | | | | W | | | | E | | | | N | | | | L | | | |
| | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 |
| First thinning | 655 | 399 | 73 | 63 | 1935 | 1311 | 77 | 30 | 1563 | 1346 | 48 | 26 | 1702 | 1686 | 84 | 33 | 473 | 246 | 158 | 59 |
| Thinning | 817 | 644 | 60 | 89 | 2595 | 2087 | 33 | 6 | 1915 | 2055 | 22 | 9 | 2223 | 2288 | 16 | 4 | 99 | 59 | 30 | 20 |
| Final cutting | 1108 | 1158 | 1462 | 1283 | 2683 | 2829 | 4958 | 4375 | 2266 | 2295 | 3967 | 3406 | 1484 | 1494 | 6586 | 6583 | 444 | 601 | 2485 | 2563 |
| | Relative area, T1=100, % (in 100 yrs) | | | | | | | | | | | | | | | | | | | |
| | S | | | | W | | | | E | | | | N | | | | L | | | |
| | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 | T1 | T2 | E1 | E2 |
| First thinning | 100 | 61 | 11 | 10 | 100 | 68 | 4 | 2 | 100 | 86 | 3 | 2 | 100 | 99 | 5 | 2 | 100 | 52 | 33 | 13 |
| Thinning | 100 | 79 | 7 | 11 | 100 | 80 | 1 | 0 | 100 | 107 | 1 | 0 | 100 | 103 | 1 | 0 | 100 | 60 | 30 | 20 |
| Final cutting | 100 | 104 | 132 | 116 | 100 | 105 | 185 | 163 | 100 | 101 | 175 | 150 | 100 | 101 | 444 | 444 | 100 | 136 | 560 | 578 |