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Energy Wood Thinning as a Part of the Stand Management of Scots Pine and Norway Spruce

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The effects of combined production of industrial and energy wood on yield and harvesting incomes, as well as the feasibility of energy wood procurement, were studied. Data for 22 Scots pine (*Pinus sylvestris* L.) and 21 Norway spruce *(Picea abies* (L.) Karst*.)* juvenile stands in Central and Southern Finland were used to compare six combined production regimes to conventional industrial wood production. The study was based on simulations made by the MOTTI stand simulator, which produces growth predictions for alternative management regimes under various site and climatic conditions. The combined production regimes included precommercial thinning at 4–8 m dominant height to a density of 3000–4000 stems ha^{-1} and energy wood harvesting at 8, 10 or 12 m dominant height. Combined production did not decrease the total yield of industrial wood during the rotation period. Differences in the mean annual increment (MAI) were small, and the rotation periods varied only slightly between the alternatives. Combined production regime can be feasible for a forest owner if the price of energy wood is 3–5 € m^{-3} in pine stands, and 8–9 € m^{-3} in spruce stands. Energy wood procurement was not economically viable at the current energy price (12 € MWh^{-1}) without state subsidies. Without subsidies a 15 € MWh^{-1} energy price would be needed. Our results imply that the combined production of industrial and energy wood could be a feasible stand management alternative.

Keywords energy wood thinning, stand management, MOTTI simulator
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1 Introduction

In Finland, good silviculture is defined as economically, ecologically and socially sustainable management of the forests. This means that the forests are being utilized and managed to obtain a sustainable profit and to maintain biological diversity (Hyvän metsänhoidon … 2006). Forest biomass is playing a crucial role in increasing the use of renewable and carbon neutral energy sources. In Finland, logging residues and nowadays also stumps from final fellings are widely used in energy production. The harvesting of energy wood from young thinning forests is encouraged by state subsidies that are designed to increase the use of energy wood, to promote silvicultural activities in young forests and, through these measures, to boost employment and the national economy. In Finland, the reserve of technically harvestable forest biomass, excluding industrial roundwood, is considered to be as much as 15 million m^3 a^{-1} (3 Mtoe) (Hakkila 2004). However, the economic viability of the procurement chains restricts the use of forest biomass and, in the year 2005, the total consumption of forest chips was around three million solid cubic meters (Ylitalo 2006). Of this amount, almost 60% was logging residues from final fellings, 20% small-sized whole tree thinning removals from young stands, and 14% stumps from final fellings (Ylitalo 2006).

Small-sized whole trees are mainly harvested from young stands approaching the first commercial thinning stage. Due to the fact that precommercial thinning has been largely neglected, these stands are currently dense and in need of thinning. However, the removal structure of the stands does not permit profitable first commercial thinning if only industrial wood is harvested. For a forest owner, whole-tree harvesting in these stands is a cost-competitive way to manage the stand. In Finland, state subsidies ensure that this type of harvesting is profitable for a harvesting company (Tanttu et al. 2004, Heikkilä et al. 2007, Ahtikoski et al. 2008). Thus, whole-tree harvesting can be a rational option in unmanaged young stands.

It is commonly acknowledged that precommercial thinning is essential in order to achieve a high industrial wood yield and sufficient stem size in the first thinning and, more generally, for favourable stand development (Varmola 1996, Ruha and Varmola 1997, Valkonen and Ruuska 2003, Varmola and Salminen 2004, Niemistö 2005, Hyvän metsänhoidon … 2006). On the other hand, the possibilities of harvesting energy wood in the first thinning are poor if precommercial thinning is carried out in the conventional manner by leaving a maximum of 2500 growing stems ha^{-1}. One aim of precommercial thinning is to achieve high industrial wood removal in the first commercial thinning, and not high energy wood removal. There appears to be a conflict between the target of increasing the use of small-sized energy wood and the target of promoting the production of industrial wood. The energy wood users are in a difficult position if their fuel procurement is based on forests in which the recommended silvicultural treatments are being neglected.

The trend towards the increasing use of energy wood started in Finland in the 1990's. Since then there have been considerable efforts to study the procurement chains of energy wood (e.g. Asikainen et al. 2001, Korpilahti 2003, Laitila et al. 2004, Äijälä et al. 2004, Kärhä et al. 2006). The problems of increased nutrient losses and other detrimental effects of whole-tree harvesting have been of interest especially in forest soil research (e.g. Olsson 1999, Jacobson et al. 2000, Nurmi and Kokko 2001, Rosenberg and Jacobson 2004). However, relatively few studies deal with forest energy production from the point of view of forest management (Hytönen 1994, Mielikäinen et al. 1995, Hytönen and Kaunisto 1999, Hytönen and Issakainen 2001, Karttunen 2006). Many of the earlier studies have focused on utilizing the low-value, broadleaf tree species that are common in peatland forests. Despite the high proportion of peatlands in Finland, about three-quarters of forest growth takes place on mineral soils (Korhonen et al. 2006). The production of good quality saw timber is the main objective on mineral soils especially. Pulpwood is harvested from stems that do not meet the diameter or quality requirements for saw timber. Energy wood is currently at the bottom of this "scale-of-values", at least in terms of stumpage prices. However, there has clearly been a downward trend in pulpwood prices in recent years (e.g. Mustonen 2006). This has to some extent been offset by the increasing demand and price of energy wood (Ylitalo 2006).

It is possible to combine industrial and energy wood production by carrying out energy wood thinning in conjunction with precommercial thinning. In addition to using the harvesting removal for energy production, integrated production also differs from conventional management in that more stems can be left growing after precommercial thinning, thus increasing the total volume growth and utilizing naturally regenerated trees. Stem size has an important impact on harvesting costs. In conventional management the desired large stem size of the harvested trees is achieved by delaying first commercial thinning. This can be achieved if the density after precommercial thinning is relatively low, i.e. between 1600–2000 stems per hectare (Huuskonen and Ahtikoski 2005, Hyvän metsänhoidon… 2006). An alternative option is to carry out light precommercial thinning, followed relatively soon by energy wood thinning, i.e. at 10–12 meters dominant height (Suihkonen 2002).

Mielikäinen (1980, 1985) studied the development of mixed pine-birch and spruce-birch stands, and found that a high birch admixture hampers the growth of pines. The growth of pine is disturbed especially when the proportion of birch is more than 20% of the total volume. In combined production the birch admixture is removed at a relatively early stand development stage, which means that the harmful effect of birch mixture on the development of pines is probably of minor importance. However, more information is still needed about the effects of growing dense, mixed pine, spruce and birch stands up until the energy wood thinning stage.

The aim of this paper is to study the alternative management regimes to combine energy wood and industrial roundwood production in young stands. The economic viability of this combined production regime during the rotation period is compared to traditional stand management in which industrial wood alone is produced. The most important task is to investigate whether the relatively high juvenile density and subsequent energy wood harvesting have a significant effect on roundwood yield at the stand level. The other task is to evaluate which management chain results in the best financial performance when combined energy and industrial wood production is applied in a stand.

2. Materials and Methods

2.1 Empirical Data

The data used in the study consisted of 22 Scots pine (*Pinus sylvestris* L.) dominated and 21 Norway spruce (*Picea abies* [L.] Karst.) dominated, unmanaged juvenile stands (Table 1, Fig. 1). The stands were used as input data for growth predictions by the MOTTI stand simulator (Salminen et al. 2005). 19 of the stands had earlier been measured for other purposes, and 24 were measured especially for this study. Two of the pine stands (P12, P13) were obtained from the study of Valkonen and Ruuska (2003), seven of the pine stands from the study of Sauvula (2006) and four of the spruce stands (S25, S26, S34, S35) from the study of Kaila et al. (2006). Seven of the pine stands (P3, P4, P9, P10, P14, P15, P20) were obtained from unpublished study.

The stands were chosen in accordance with the following criteria:

- The main tree species was pine or spruce
- The stand was located on mineral soil
- The site fertility class, based on the forest site types of Cajander (1949), of the pine stand was dryish or fresh (Tonteri et al. 1990)
- The site fertility class of the spruce stand was fresh or grovelike (Tonteri et al. 1990)
- No precommercial thinning had been carried out
- The first commercial thinning was not imminent
- The total density was over 4000 stems ha^{-1}
- The temperature sum* class was either 1150–1300, 1000–1150 or 850–1000 degree days.

* Long-term average, effective temperature sum (threshold +5°C), according to the model of Ojansuu and Henttonen (1983)

The stands were located between latitude 61–65°N, and longitude 22–29°E (Fig. 1). The aim was to evaluate management alternatives throughout the whole of Finland, apart from the northernmost area where forestry is of little importance. Eight of the pine stands had been naturally regenerated, seven seeded and seven planted. All of the spruce stands had been planted. The stands consisted of a varying mixture of conifers and broadleaved species, because virtually no silvicultural treatments had been carried out after regeneration. The pine stands were divided into

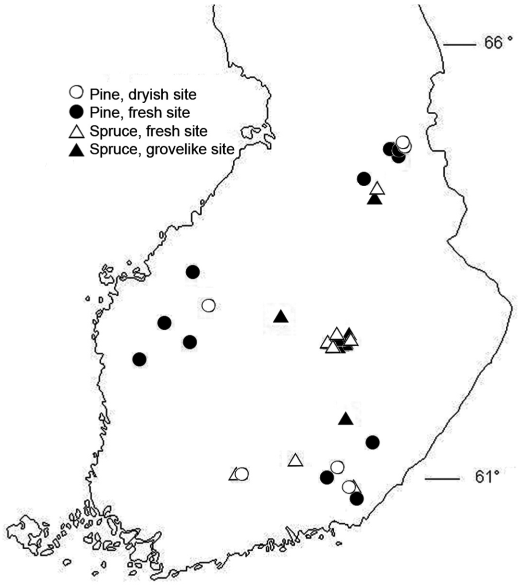

Fig 1. Location of the stands.

two categories according to the species mixture and the stem number of pine. The first pine stand category and all the spruce stands (stands P1–P11 and S23–S43) included a significant admixture of broadleaved trees. In the simulations, they were grown as mixed forests between the precommercial thinning and the energy wood thinning. The second category of pine stands (P12–P22) consisted of pine-dominated young stands, with the stem number of pines more than 4000 trees per hectare. They were simulated as pure pine stands.

Because the data were obtained from several sources, there was some variation in the sample plot size and measured tree parameters. The minimum sample plot area in our study material was 154 m^2, and the total number of measured trees required to represent the stand was at least 62. The 24 stands were measured especially for this study as follows: Three circular ($r = 5$ m) sample plots were placed systematically on the longest diagonal line of the stand. The tally trees with height over 1.3 m were measured for breast height diameter and tree species. All the trees within radius of three meters from the centre of sample plot were sample trees and were measured for tree height, crown height and age. The seven pine stands obtained from the unpublished study were measured according TINKA experiments as follows: Three circular ($r = 7$) sample plots were placed systematically in the stand and all trees over 1.3 m height were measured for breast height diameter, tree species, height and crown height (Gustavsen et al. 1988).

Based on the sample tree measurements, tree heights and crown heights were predicted for the tally trees using the KPL-software package developed by the Finnish Forest Research Institute (Heinonen 1994). These data were then used as the input data for the MOTTI simulator. The tree characteristics of the input data included tree species, stem number, age, diameter, height, and crown ratio of the trees by diameter class. The main stand characteristics estimated in the field measurements and used as stand input variables were site type, regeneration method, and location.

2.2 Stand Projections

Growth and yield of the stands were estimated according to different management schedules by means of simulations performed with the MOTTI simulator. MOTTI is a stand-level simulator, in which stand dynamics (growth, mortality and natural regeneration) is predicted by means of statistical growth and yield models. MOTTI is designed to simulate stand development under alternative management regimes and growth conditions in Finland (Hynynen et al. 2005, Salminen et al. 2005). In the MOTTI simulator the user can define the different parameters of the simulations. For instance, management schedule, stumpage prices, unit costs for logging and discount rate are user definable. The reliability of the simulation results of MOTTI has been tested in earlier studies. The performance of the MOTTI simulator has been assessed in young Scots pine stands by Ahtikoski et al. (2004), Huuskonen (2008) and Huuskonen and Ahtikoski (2005), and in mixed stands by Hynynen et al. (2002). Mäkinen et al. (2005) evaluated the reliability of the growth predictions in intensively managed Scots pine stands. The results indicate that the MOTTI simulator can be applied as a tool to compare stand management alternatives in Finnish conditions.

Table 1. Stand parameters.

Stand	Regeneration method	Temperature sum, d.d.	Total age, a	H_{dom}, m	N_{pine}	$N_{broadl.}$	N_{spruce}	N_{tot}
SCOTS PINE STANDS WITH BIRCH ADMIXTURE								
Dryish site								
P1	Planting	1274	14	4.8	2 339	8 445	0	10 784
P2	Planting	1244	15	4.4	2 209	12 147	130	14 486
P3	Natural	1105	10	4.1	10 822	2 886	0	13 708
P4	Natural	1119	11	5.4	8 785	3 947	0	12 732
P5	Direct sowing	945	25	8.1	3 989	5 348	42	9 379
P6	Direct sowing	938	21	7.3	5 135	7 130	42	12 307
Average		1104	16.0	5.7	5 547	6 651	36	12 233
Fresh site								
P7	Planting	1267	13	5.2	2 468	7 925	0	10 393
P8	Planting	1242	12	4.4	2 988	5 197	0	8 185
P9	Natural	1105	12	5.5	1 443	4 541	340	6 324
P10	Natural	1119	11	5.8	5 517	4 796	42	10 355
P11	Direct sowing	953	26	8.2	5 602	2 674	42	8 318
Average		1137	14.8	5.8	3 604	5 027	85	8 715
SCOTS PINE STANDS								
Dryish site								
P12	Planting	1257	12	5.4	4 329	4 839	159	9 327
P13	Planting	1257	12	4.0	4 552	5 284	32	9 868
P14	Natural	1093	13	5.9	5 517	7 342	85	12 944
P15	Natural	1090	12	5.2	8 912	2 801	255	11 968
P16	Natural	1008	14	5.2	8 573	255	0	8 828
P17	Planting	951	17	4.7	4 930	2 121	0	7 051
Average		1109	13.3	5,1	6 136	3 774	89	9 998
Fresh site								
P18	Direct sowing	1241	10	3.9	6 578	3 438	0	10 016
P19	Direct sowing	1253	13	4.9	8 403	7 979	2 801	19 183
P20	Natural	1068	12	4.3	5 560	891	0	6 451
P21	Direct sowing	954	25	7.6	5 432	1 231	0	6 663
P22	Direct sowing	950	15	4.9	7 003	891	0	7 894
Average		1093	15.0	5.1	6 595	2 886	560	10 041
Average		**1111**	**14.8**	**5.4**	**5 504**	**4 641**	**180**	**10 326**
St.dev.		**127**	**4.9**	**1.3**	**2 487**	**2 969**	**592**	**3 092**
NORWAY SPRUCE STANDS WITH BIRCH ADMIXTURE								
Fresh site								
S23	Planting	1201	15	4.2	130	3 768	2 793	6 691
S24	Planting	1198	15	5.6	0	2 208	1 819	4 027
S25	Planting	1287	16	6.5	199	6 814	2 984	9 997
S26	Planting	1265	14	6.4	298	11 582	3 479	15 359
S27	Planting	1193	14	4.4	127	3 438	3 862	7 427
S28	Planting	1151	10	3.4	1 825	8 106	1 103	11 034
S29	Planting	1163	14	5.6	1 273	8 404	1 528	11 205
S30	Planting	1139	12	4.9	2 801	13 157	1 698	17 656
S31	Planting	1105	14	6.1	2 801	7 045	3 735	13 581
S32	Planting	948	15	4.8	0	10 227	3 013	13 240
S33	Planting	970	17	6.2	42	12 302	2 504	14 848
Average		1147	14.2	5.3	863	7 914	2 593	11 370
Grovelike site								
S34	Planting	1184	17	5,7	891	5 030	2 101	8 022
S35	Planting	1184	19	6,5	0	13 373	3 280	16 653
S36	Planting	1245	12	4,1	340	3 905	2 377	6 622
S37	Planting	1195	10	3,5	382	24 446	1 485	26 313
S38	Planting	1149	12	3,7	0	9 847	1 273	11 120
S39	Planting	1140	12	5,1	0	16 934	1 443	18 377
S40	Planting	1172	11	5,4	509	15 991	1 698	18 198
S41	Planting	1116	12	5,3	127	6 281	1 995	8 403
S42	Planting	977	24	8,8	0	10 738	1 867	12 605
S43	Planting	983	24	8,4	0	5 942	2 546	8 488
Average		1135	15.3	5.7	225	11 249	2 007	13 480
Average		**1141**	**14.7**	**5.5**	**559**	**9 502**	**2 313**	**12 375**
St.dev.		**96**	**3.9**	**1.4**	**882**	**5 371**	**835**	**5 232**

In order to estimate the effect of whole-tree harvesting on stand development, MOTTI was customized to predict also the growth reduction due to the nutrient loss associated with whole-tree harvesting. The growth reduction was estimated on the basis of the dry mass and nitrogen concentration of the harvested tree compartments. The nitrogen loss was also converted to the percentual growth loss on the basis of empirical experiments on the effect of whole-tree harvesting (Jacobson et al. 2000).

Seven management alternatives combining different precommercial thinning and first thinning methods were created. Stand development during the whole rotation period was simulated for each of the alternatives. The alternatives were:

Alternative IWP_1: Industrial wood production according to the silvicultural recommendations (Hyvän metsänhoidon… 2001)

- Stem number after precommercial thinning 2000 stems ha^{-1} in pine stands, and 1800 stems ha^{-1} in spruce stands
- First commercial thinning at dominant height of 11–13 m in pine stands, and at 13 m in spruce stands. The exact time of thinning was determined on the basis of the basal area and dominant height.
- Stem number after the first commercial thinning 1000 stems ha^{-1} in pine stands, and 900 stems ha^{-1} in spruce stands

Alternatives CP_2–CP_7: Combined production regimes using all the six possible combinations of the following management alternatives

- Stem number after precommercial thinning 3000 or 4000 stems ha^{-1}
- Energy wood thinning at dominant height of 8, 10 or 12 m to leave 1300 pine or spruce stems ha^{-1}

In combined production (CP_2–CP_7) for pine stands (P1–P11), 2000 pine stems ha^{-1} was left in precommercial thinning and, in order to meet the total density criterion (3000 or 4000 ha^{-1}), silver birches (*Betula pendula* Roth) or downy birches (*Betula pubescens* Ehrh.) were left growing. The P12–P22 stands were managed as pure pine stands. All the spruce stands (S23–S43) were managed as mixed stands between precommercial thinning and energy wood thinning. The

Table 2. Management alternatives. (PCT = precommercial thinning).

Management alternative	PCT density, stems ha^{-1}	Time of first/energy wood thinning, h_{dom}, m
IWT_1	1800–2000	11–13
CP_2	3000	8
CP_3	3000	10
CP_4	3000	12
CP_5	4000	8
CP_6	4000	10
CP_7	4000	12

purpose of splitting the pine data was to assess the possibilities of growing both pine and birch stems for energy wood. Because planting, which is usually applied on more fertile sites, is the most expensive regeneration method in Finland, it does not seem economically justified to harvest planted trees for low-value energy wood. However, if we could harvest naturally regenerated broadleaved trees (which normally occur on planting sites) for energy, we could also apply energy wood harvesting on fertile sites.

All the existing broadleaved trees were removed in the energy wood thinning. Thereafter, the stands were simulated as pure coniferous stands during the rest of the rotation period. In conventional industrial wood production (IWP_1) all the broadleaved trees were removed already in precommercial thinning.

The timing of the final felling was determined by the average stem diameter according to Finnish silvicultural recommendations for private forests (Hyvän metsänhoidon…2006). The diameter criterion is determined by tree species, site type and location of stand. In our study, it varied between 24–30 cm.

2.3 Financial Analyses

2.3.1 Forest Owner's Profitability

Forest owners make their managerial decisions on the basis of numerous criteria, of which economical profitability is usually the most important one. Therefore, the profitability of different management alternatives during the rotation period was first determined from the forest owner's point of

Table 3. Applied minimum top diameter of timber assortments and stumpage prices.

Timber assortment	Min. top diameter, cm	First thinning	Other harvests
		Stumpage price, € m^{-1}	
Pine saw log	15	–	44
Spruce saw log	16	41	46
Birch saw log	18	–	40
Spruce pulp wood	7	17	21
Pine & birch pulp wood	6	10	12

view. The cutting incomes were discounted to the time of precommercial thinning, which is the time when the choice between the management alternatives studied in this paper actually takes place. The current values were calculated as follows:

$$PW_{im} = \sum_{h}^{H} \frac{I_{imh}}{\left(1+r\right)^{t_{imh}}} \quad \text{(Eq. 1)}$$

where

PV_{im} = present value of cutting incomes over the rotation period at the time of precommercial thinning in stand *i* according to management alternative *m*, *i* = P1, P2, ...S43, *m* = IWP_1, CP_2, ...CP_7

I_{imh} = cutting income of stand *i* and management alternative *m* by harvest number *h*, *h* = 1 (first thinning), 2 (second thinning), 3 (third thinning), 4 (fourth thinning) or *H* (final cut)

r = discount rate: 1, 3 or 5% (expressed as decimal digit in the formula)

t_{imh} = time from precommercial thinning, years

The stumpage prices used in the study were based on the 2005 level in Finland, excluding Northern Finland where the stumpage prices are clearly lower than in the rest of the country (Table 3) (Puukauppa – puun ostot… 2006). The stumpage prices in first commercial thinnings tend to be lower than those in later thinnings and in final fellings because of the high harvesting costs, which are due to the low stem volumes and low cutting removals. Thus lower stumpage prices were applied for first commercial thinnings. In first commercial thinnings in pine stands, no saw timber was harvested because the quality requirements of saw timber are not usually met (Vuokila and Väliaho 1980). In the basic scenario, the stumpage price of energy wood was 3 € m^{-3}. In energy wood thinning all the removal, including industrial-sized stem wood, was considered as energy wood. A sensitivity analysis was also carried out for energy wood prices of 3, 5 or 7 € m^{-3}. The profitability of the combined production chains (CP_2–CP_7) was also calculated for the integrated harvesting of energy and industrial wood in the first thinning, i.e. the pulp wood was harvested separately from energy wood.

2.3.2 Bare Land Value Analysis

Due to the fact that the rotation periods between the management alternatives varied among the stands, we needed to test the robustness of the original present values determined by Eq. 1 by applying Faustman's rotation model (e.g. Hyytiäinen and Tahvonen 2001). For simplicity, we calculated the bare land values only for the dryish site type, in which the rotation periods fluctuated the most (see Table 4). We adopted the so-called discrete form of Faustman's rotation model (Hyytiäinen and Tahvonen 2001) when calculating the bare land values:

$$BL_F = \frac{\sum_{i=0}^{l} CI_i \times (1.0r)^{-i} - \sum_{i=0}^{n} SC_{ik} \times (1.0r)^{-i}}{1-(1.0r)^{-l}} \quad \text{(Eq. 2)}$$

where

BL_F = value of the bare land, € ha^{-1}

CI_i = cutting income at stand age *i*, € ha^{-1} (*l* indicates rotation period)

SC_{ik} = silvicultural cost for activity *k* at stand age *i*, (for establishment costs *i* = 0 and *k* =1), Note: since cutting costs are excluded, *l* > *n* r = discount rate (real rate, i.e. net of inflation)

For the establishment cost (SC_{01}) of a pine stand on the dryish site type we applied an average direct seeding cost of 183 € ha^{-1} (Metsänhoito- ja perusparannustöiden … 2007). In addition, the cost of clearing the regeneration area was 138 € ha^{-1} (Metsänhoito- ja perusparannustöiden … 2007). We did not include the tending of sapling stands in the calculations because the stands in the study data were unmanaged. When calculating the bare land values we used the same industrial wood stumpage prices as when determining the PVs (Eq. 1). The energy wood stumpage price was 3 € m^{-3}. For the analysis we chose four dryish site type pine stands, representing two climatic regions: Southern (1150–1300 d.d.) and Northern (850–1000 d.d.) Finland. Finally, we compared the original results (PVs) to the bare land values with respect to two management alternatives, namely industrial wood production (IW_P) and combined production (CP_3).

2.3.3 Feasibility Approach to Energy Wood Procurement

Even though the forest owner makes the management decisions, the profitability must also be determined from the perspective of the other players involved in energy wood procurement. If there was no possibility to realize a profit, the other players would not participate in the production. Therefore, we need to analyze the energy wood procurement first as an entity, and then to determine the possible profits pertaining to different actors, such as private forest owner, contractor and power plant (see e.g. Tharakan et al. 2005). We assessed energy wood thinning from this perspective by calculating the overall financial viability, i.e. the feasibility of energy wood procurement from forest to the power plant (Eq. 3). This methodology reveals whether the constructed management alternatives were also feasible in the actual market conditions. If the supply chain of energy wood turns out to be too expensive, i.e. the procurement costs exceed the power plant's paying capacity, then the whole business chain would fail. Because there are virtually no doubts about the financial feasibility of the conventional industrial wood supply chain, this feasibility study was applied only for energy wood thinning.

$$P_{im} = (I_{im} + VCSS_{im} - VCC_{im})ewr + ACSS_{im} - ACC_{im} \quad \text{(Eq. 3)}$$

where

P_{im} = profit (€ ha^{-1}) of stand i according to management alternative m, i = P1, P2, ...S43, m = CP_2, CP_3, ...CP_7

I_{im} = income from selling energy wood to power plant, € m^{-3}

$VCSS_{im}$ = state subsidies for energy wood thinning based on harvested volume, € m^{-3}

$ACSS_{im}$ = state subsidies for energy wood thinning based on harvested area, € ha^{-1}

VCC_{im} = costs of energy wood procurement based on harvested volume, € m^{-3}

ACC_{im} = costs of energy wood procurement based on harvested area, € ha^{-1}

ewr = energy wood removal, m^3 ha^{-1}

The harvesting cost of energy wood was calculated using the functions of Laitila et al. (2004). A cost of 5 € m^{-3} for roadside chipping and 5 € m^{-3} for long distance transportation was used (40 km transport distance). A fixed cost of 50 € per stand for the translocation of a harvester, forwarder and chipper from one harvesting site to another was also used (totaling 150 € per stand). For example, Väätäinen et al. (2006) calculated that the average translocation cost of a harvester-forwarder chain from one stand to another was 171 €. The organization costs of the procurement company, including purchasing the wood, were 4 € m^{-3}.

As whole-tree chips are used both in large-scale combined heat and power production (CHP) and in medium- to small-scale heat production, the price of whole-tree chips is by no means a matter-of-course. The average price of forest chips, which primarily consists of logging residue chips from final fellings, can be considered as the minimum energy wood price. This was about 12 € MWh^{-1} at the end of 2005 (Ylitalo 2006). The fuel prices used in the feasibility study were 12 (basic scenario), 15 and 18 € MWh^{-1}.

State subsidies were included in the feasibility study. The total amount of subsidies is the sum of numerous types of subsidy granted to the different players for a range of reasons (Valtion tuet… 2006). In the southern parts of Finland the state subsidy for young stand treatment (h_{dom} 8–15 m) is 250 € ha^{-1}. In addition to this, 7 € m^{-3} (solid) is paid for harvested energy wood and 1.7 € for chipped m^3 (loose). In this study the total amount of subsidies varied from 12.5 to 28.3 € m^{-3}. The feasibility of the energy wood procurement was also calculated without any subsidies.

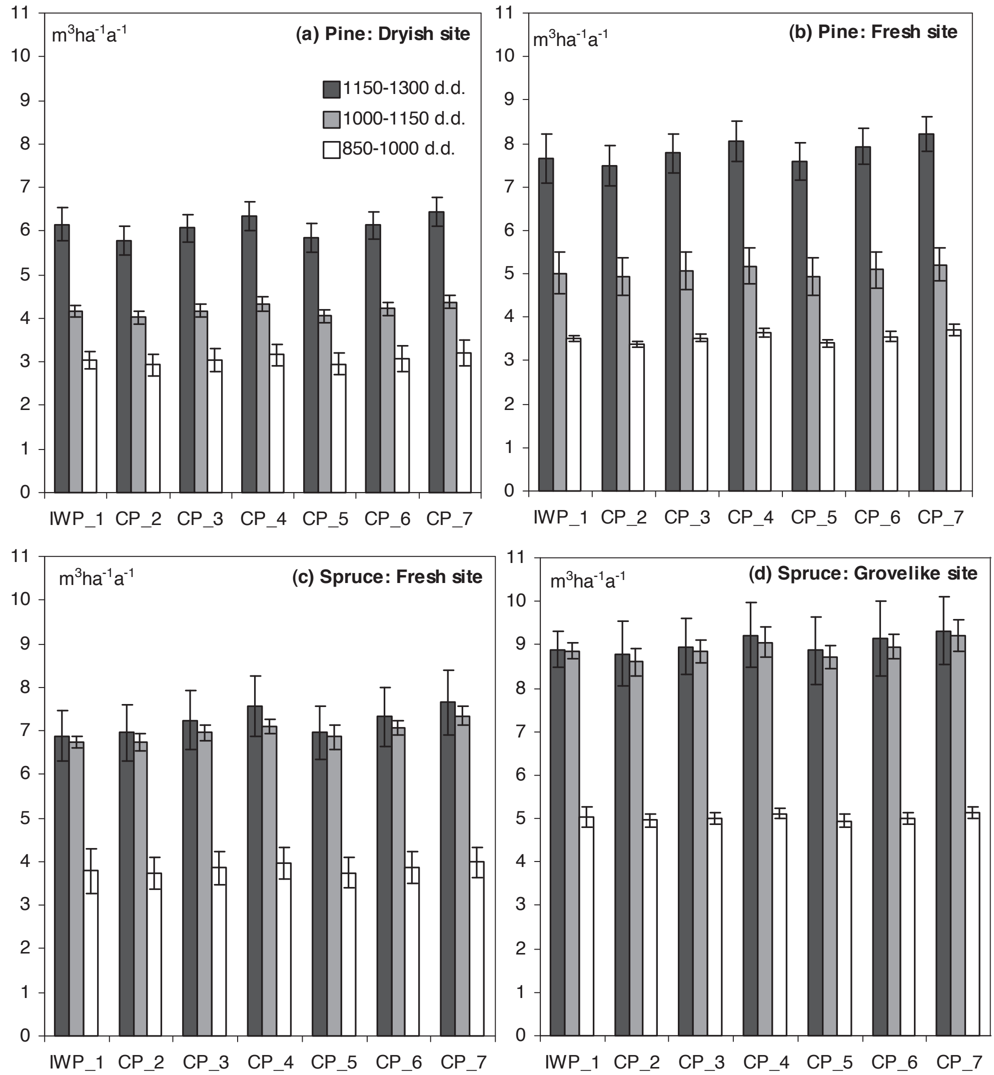

Fig. 2. Mean annual increment (MAI) of stem wood by different management alternatives and temperature sum classes.

3 Results

3.1 Growth and Yield

The effect of the management regime had only a negligible effect on the predicted growth and yield of the studied stands (Tables 4 and 5, Fig. 2). The average annual growth varied only slightly between the management alternatives, but the tree species and especially the temperature sum had an important effect on growth, as expected. In the case of the spruce stands, there were no growth differences between the southernmost temperature classes. This was probably due to the fact that the stands in d.d.-class 1000–1150 were located close to each other (Fig. 1) in an area with especially favourable growth conditions. The management regimes in which the growing stock was kept at a higher level by leaving more stems in precommercial thinning or delaying energy

Table 4. Harvested volumes, total stem wood yield and rotation period by different management chain and temperature sum in the pine stands. (DD = degree days).

Stand	Management alternative	First thinning/ energy wood thinning			Later thinnings		Final felling		Total yield	Rotation period
		Saw timber	Pulp-wood	Energy wood	Saw timber	Pulp-wood	Saw timber	Pulp-wood		
SCOTS PINE STANDS										
Dryish site										
D.D. class	IWP_1	–	59	0	16	38	230	72	445	73
1150–1300	CP_2	–	22	28	41	68	173	52	385	67
Stands:	CP_3	–	46	31	43	70	177	54	419	69
P1,P2,P12,P13	CP_4	–	72	33	43	73	186	56	464	73
	CP_5	–	22	35	40	68	175	52	392	67
	CP_6	–	47	39	42	71	181	54	432	71
	CP_7	–	74	40	45	73	188	55	479	75
D.D. class	IWP_1	–	54	0	19	38	222	78	461	111
1000–1150	CP_2	–	16	24	44	69	176	58	410	102
Stands:	CP_3	–	41	27	46	71	179	62	447	107
P3,P4,P14,P15	CP_4	–	66	29	47	73	181	64	484	112
	CP_5	–	16	31	46	69	174	57	414	102
	CP_6	–	44	36	47	71	176	61	454	108
	CP_7	–	73	37	48	74	179	62	497	114
D.D. class	IWP_1	–	46	0	14	32	151	74	360	119
850–1000	CP_2	–	12	21	25	51	133	64	327	112
Stands:	CP_3	–	28	22	23	52	136	66	351	115
P5,P6,P16,P17	CP_4	–	46	22	22	53	141	70	381	121
	CP_5	–	14	26	25	51	133	64	331	112
	CP_6	–	31	29	23	52	136	66	357	116
	CP_7	–	51	27	23	54	141	70	394	123
Fresh site										
D.D. class	IWP_1	–	68	0	66	76	226	66	525	69
1150–1300	CP_2	–	24	29	48	83	265	78	525	70
Stands:	CP_3	–	56	32	49	88	274	81	572	74
P7,P8,P18,P19	CP_4	–	88	38	50	92	287	79	622	77
	CP_5	–	25	40	47	84	269	79	539	71
	CP_6	–	62	44	48	90	279	83	593	75
	CP_7	–	100	46	51	94	293	77	647	79
D.D. class	IWP_1	–	61	0	72	70	227	66	508	102
1000–1150	CP_2	–	13	23	53	79	270	79	511	104
Stands:	CP_3	–	31	26	53	81	276	82	540	107
P9,P10,P20	CP_4	–	55	29	73	89	249	79	563	109
	CP_5	–	13	28	54	78	270	79	516	105
	CP_6	–	32	32	56	81	273	81	546	108
	CP_7	–	58	34	73	89	250	80	573	110
D.D. class	IWP_1	–	50	0	30	54	175	67	409	116
850–1000	CP_2	–	11	21	22	60	196	75	395	117
Stands:	CP_3	–	31	26	37	75	169	64	407	116
P11,P21,P22	CP_4	–	58	29	37	76	174	67	442	121
	CP_5	–	12	29	22	61	200	75	400	118
	CP_6	–	35	36	37	75	171	65	416	117
	CP_7	–	64	37	37	77	178	68	458	124

Table 5. Harvested volumes, total stem wood yield and rotation period by different management chain and temperature sum in the spruce stands. (DD = degree days).

Stand	Management alternative	First thinning/ energy wood thinning			Later thinnings		Final felling		Total yield	Rotation period
		Saw timber	Pulp-wood	Energy wood	Saw timber	Pulp-wood	Saw timber	Pulp-wood		
SPRUCE STANDS										
Fresh site										
D.D. class	IWP_1	9	42	0	32	32	197	53	389	57
1150–1300	CP_2	0	11	27	11	36	253	65	406	59
Stands:	CP_3	1	32	37	12	37	260	63	437	61
S23–S27	CP_4	4	59	44	15	38	272	62	481	64
	CP_5	0	12	33	12	36	249	65	406	59
	CP_6	1	36	44	13	36	262	64	448	61
	CP_7	4	68	52	15	38	271	63	494	65
D.D. class	IWP_1	8	39	0	32	33	201	55	392	58
1000–1150	CP_2	0	5	23	12	39	252	63	403	60
Stands:	CP_3	1	19	29	12	39	266	61	430	62
S28–S31	CP_4	3	32	33	15	42	264	56	444	63
	CP_5	0	7	30	12	39	261	60	415	61
	CP_6	1	27	38	15	42	261	56	438	62
	CP_7	2	48	44	16	42	270	58	474	65
D.D. class	IWP_1	5	36	0	25	28	184	61	340	90
850–1000	CP_2	0	5	25	12	33	193	63	339	91
Stands:	CP_3	1	18	31	12	33	196	64	358	94
S32,S33	CP_4	3	34	36	14	33	195	66	380	97
	CP_5	0	5	28	13	34	190	62	339	91
	CP_6	1	18	35	13	33	192	64	360	94
	CP_7	3	36	39	13	33	195	66	384	97
Grovelike site										
D.D. class	IWP_1	10	46	0	33	27	328	65	530	60
1150–1300	CP_2	0	17	30	32	48	340	63	527	60
Stands:	CP_3	1	37	37	44	53	326	59	547	61
S34–S37	CP_4	5	59	44	45	55	330	60	580	63
	CP_5	0	19	36	32	47	343	63	536	61
	CP_6	1	42	44	34	48	356	59	572	63
	CP_7	5	67	50	46	55	335	56	596	64
D.D. class	IWP_1	8	47	0	35	26	334	61	529	60
1000–1150	CP_2	0	8	23	53	62	284	69	501	58
Stands:	CP_3	1	24	29	52	63	309	58	531	60
S38–S41	CP_4	3	44	35	53	64	317	54	559	62
	CP_5	0	10	30	53	62	292	65	511	59
	CP_6	0	29	36	54	64	317	52	546	61
	CP_7	2	53	42	55	65	326	54	585	64
D.D. class	IWP_1	4	31	0	26	27	210	70	373	74
850–1000	CP_2	0	4	20	13	33	216	71	367	74
Stands:	CP_3	0	9	24	13	33	217	71	376	75
S42,S43	CP_4	1	22	29	13	33	218	73	392	77
	CP_5	0	4	23	13	33	216	71	367	74
	CP_6	0	10	27	13	32	216	72	375	75
	CP_7	1	23	32	14	33	221	71	396	77

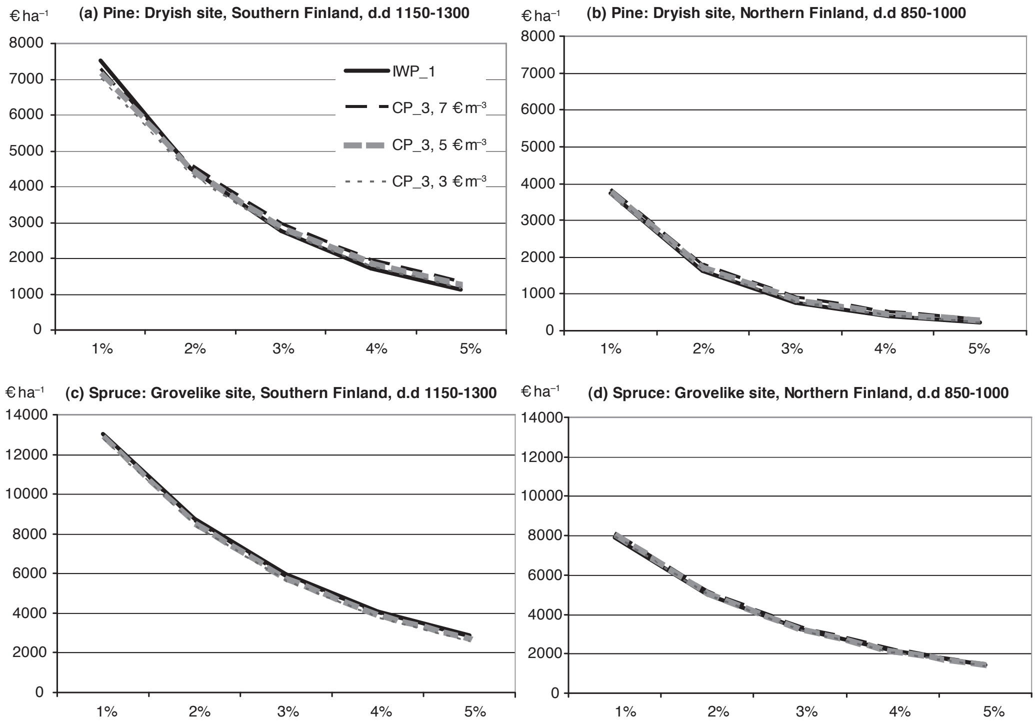

Fig. 3. Present values of cutting incomes of industrial wood production (IWP_1) and combined production regime (CP_3) by different interest rate and energy wood price (3, 5 or 7 € m^{-3}) in Southern and Northern Finland.

wood thinning, resulted in a slightly increased mean annual increment. Natural mortality also varied between the management chains. Delaying the energy wood thinning increased the natural mortality.

As the criterion for the timing of final felling was mean stem diameter, the rotation period of the stands varied slightly under the different management chains (Tables 4 and 5). In the pine stands, conventional management led to a rotation period that was a few years longer than that of combined management on dryish sites, and few years shorter on fresh sites. In the spruce stands the rotation period was somewhat longer in combined management.

3.2 Forest Owner's Profitability

There were no major differences in the current size of the harvesting incomes between the management alternatives (Fig. 3). In the pine stands on dryish sites, the incomes of the combined management chain (CP_3) were higher than those of the conventional management chain, when the stumpage price of energy wood was 3 € m^{-3} or higher and the discount rate at least 3%. On fresh sites the combined management chain was feasible with a somewhat higher (5 € m^{-3}) energy wood price. In the spruce stands the combined production was profitable with energy wood prices above 8 € m^{-3}.

The small differences between the studied management alternatives can be explained by the fact that cutting incomes from first thinning account for less than one fifth of the total income over the rotation period. The higher the interest rate, the smaller is the difference between the present

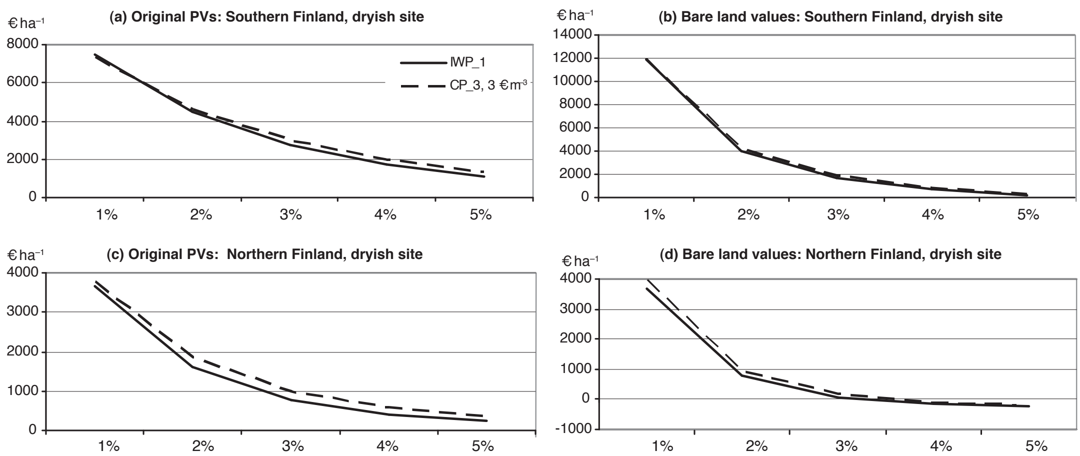

Fig 4. Original present values (PVs) in Southern (a) and Northern Finland (c) compared to bare land values (b and d), respectively.

values of the different management alternatives. Using low interest rates such as 1–2% favoured the management alternatives with a long rotation period, and vice versa.

Decreasing the industrial wood prices by 20% in first commercial thinning stands increased the profitability of combined production: in pine stands the break-even energy wood price was 1.5–4 € m^{-3} and in spruce stands 5.5–7 € m^{-3}. Increasing the industrial wood prices by 20% had the opposite effect on profitability. If the energy wood thinning is carried out using integrated harvesting of industrial and energy wood, then the break-even energy wood price was negative in pine stands and 0–3 € m^{-3} in spruce stands.

3.3 Bare Land Value Analysis

The results of sensitivity analyses indicated that the original PVs and bare land values behaved in a similar manner (Fig. 4 a–d). This confirms that the financial outcomes of industrial wood production and combined production management regimes do not diverge considerably from each other, regardless of whether present valuation or bare land valuation, i.e. the Faustman rotation model, is applied.

3.4 Feasibility of Energy Wood Procurement

The cutting and forest transportation costs of first thinning were markedly affected by stand properties, especially the average tree size (Table 6). Delaying energy wood harvesting sharply decreases the costs. In whole-tree harvesting the harvested volume/tree is greater than that in industrial wood harvesting, and therefore the cost of energy wood harvesting is lower.

As the stand properties have a strong effect on harvesting costs they also influence the feasibility of the different supply chains (Fig 5). When energy wood harvesting is carried out at an 8 m dominant height, the total economical viability was low with an energy price of 12 € MWh^{-1}. This means that the procurement chain is not feasible and will most likely never be used. The total profit of a procurement chain has to be over 200 € ha^{-1} in order to ensure the ability to pay a decent (3–5 € m^{-3}) stumpage price to the forest owner. This was the case in management alternatives CP_4 and CP_7. State subsidies were essential for economical viability. If there were no subsidies, a price of 15 € MWh^{-1} or more would be needed.

Table 6. Average cutting and forest haulage costs in first thinning by management alternative.

Management alternative	All pine stands Tree size, dm³	Cutting cost, € m⁻³	Forwarding cost, € m⁻³	All spruce stands Tree size, dm³	Cutting cost, € m⁻³	Forwarding cost, € m⁻³
IWP_1	67	12,0	4,0	58	13,7	4,3
CP_2	26	14,9	4,8	22	20,4	5,0
CP_3	46	10,0	4,5	38	14,0	4,6
CP_4	74	7,7	4,3	61	10,9	4,4
CP_5	20	15,3	4,7	17	21,2	4,9
CP_6	36	10,4	4,4	31	14,5	4,5
CP_7	60	8,0	4,3	51	11,2	4,3

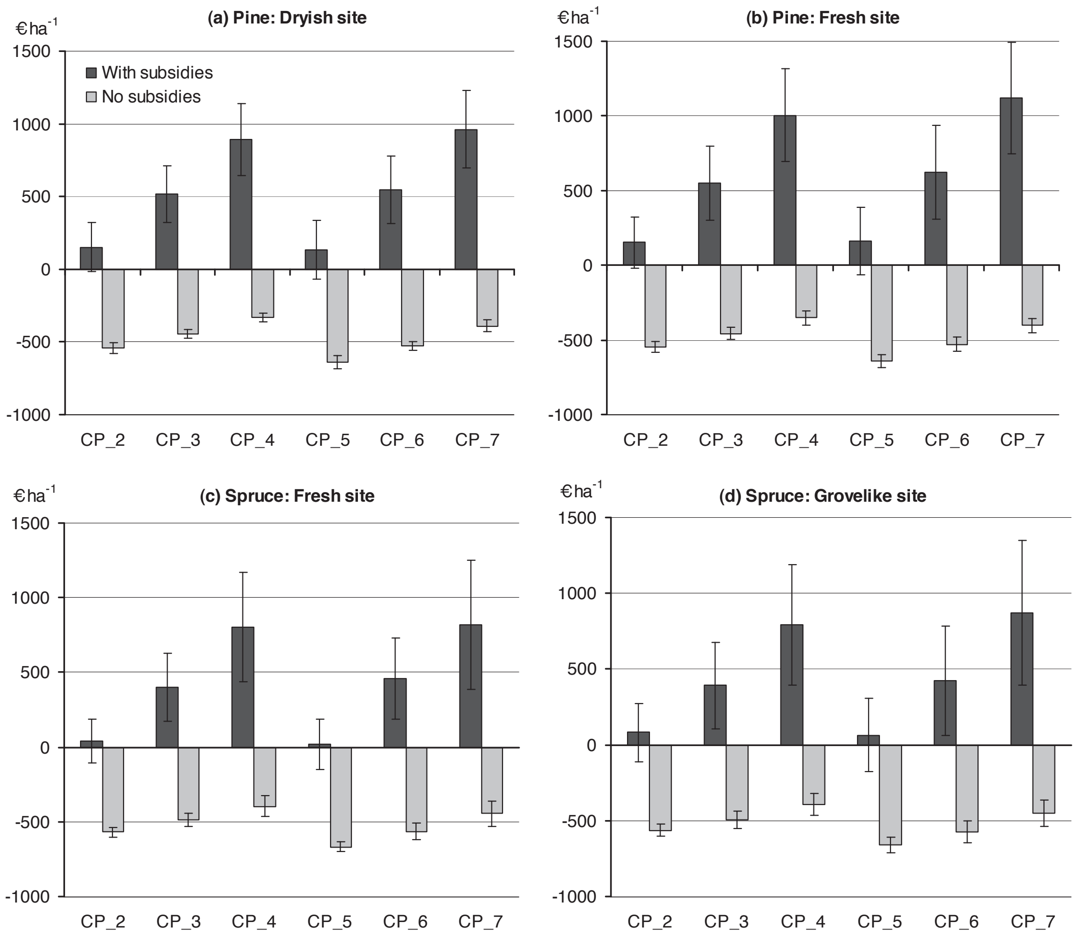

Fig 5. Feasibility of energy wood procurement.

4 Discussion

Combined production did not decrease the possibilities to produce industrial wood. There were no major differences in the mean annual increments or in the rotation periods between the management alternatives. For a private forest owner, combined production regime can be financially justified if the stumpage price of energy wood is 3–5 € m^{-3} in pine stands, and 8–9 € m^{-3} in spruce stands. Integrated harvesting of energy and industrial wood can significantly decrease the above-mentioned break-even prices if the harvesting costs remain reasonable. Energy wood procurement was not economically viable without state subsidies at the current energy price. With subsidies, all the combined production alternatives were profitable. However, without subsidies an energy price of 15 € MWh^{-1} would be needed and, even then, only the best combined production alternatives were profitable.

Different types of forest management result in different harvesting conditions. Harvesting conditions have a significant influence on harvesting productivity, costs, the silvicultural harvesting result and even on the stumpage price. Reasonable harvesting conditions for both energy wood thinning and first industrial wood thinning can be achieved at the same time in combined production. According to Salo (2004), a minimum removal of 30 m^3 ha^{-1} and an average stem size of 20–30 dm^3 are needed for profitable harvesting in mechanized energy wood thinning.

The findings of this study are conditional on the reliability of the applied simulation method. The growth and yield models applied in the MOTTI simulator have been developed to be applicable in the most common stand types and structures in Finland, including mixed stands (Hynynen et al. 2002). The growth and yield models of MOTTI have been fitted to extensive measurement data from forest inventory growth plots (INKA and TINKA) (Gustavsen et al. 1988). The modelling data are a sample from commercial forests, not from specially designed experiments. Therefore, extreme treatments such as a very dense or sparse stands are relatively poorly represented in the data. The crucial model property affecting the reliability of the results of this study is how reliably the models can predict the effect of stand density on the growth of young stands. So far, the models of the MOTTI simulator have been tested against empirical data from stands at the first commercial thinning stage (Huuskonen and Ahtikoski 2005, Mäkinen et al. 2005). No notable biases with respect to thinning treatments were found in those studies. In general, however, the growth prediction of young stands is a challenging task for growth and yield modelling.

The simulation results of different management scenarios were compared in this study. No statistical tests were applied in the analysis, because the simulated data do not meet the data requirements for statistical analysis.

The growth decline caused by whole-tree harvesting was predicted solely on the basis of the nitrogen loss, without considering other possible effects on growth. The model applied in MOTTI for predicting the growth response can be regarded as a preliminary model. The data used in estimating growth decline were based on a relatively limited empirical data collected from long-term experiments established for assessing the growth response to whole-tree harvesting in Scots pine and Norway spruce stands (Jacobson et al. 2000).

The annual energy wood potential is considerably high if combined production regime were to be widely adopted in Finland. According to the national forest inventory (NFI9), there are annually about 130 000 hectares of forest in need of precommercial thinning and combined production could be applied in these forests (Valtakunnan metsien … 2008). The results of this study suggest that combined management can be a reasonable wood production alternative. It is obvious that combined management is a feasible alternative only in areas where the energy wood users are located. Scots pine stands located relatively close to energy wood users could be the first areas for combined management.

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References

Ahtikoski, A., Päätalo, M.-L., Niemistö, P., Karhu, J. & Poutiainen, E. 2004. Effect of alternative thinning intensities on the financial outcome in silver birch (Betula pendula Roth) stands: a case study based on long-term experiments and MOTTI stand simulations. Baltic Forestry 10(2): 46–55.

— , Heikkilä, J., Alenius, V. & Sirén, M. 2008. Economic viability of utilizing biomass energy from young stands – the case of Finland. Biomass and Bioenergy 32(11): 988–996.

Äijälä, O., Fredriksson, T., Kuusinen, M. & Poikela, A. 2004. Koneellisen energiapuun korjuun laadunseurannan kehittämisprojektin (KELK) loppuraportti. Metsätalouden kehittämiskeskus Tapio 40 p. (In Finnish).

Asikainen, A., Ranta, T., Laitila, J. & Hämäläinen, J. 2001. Hakkuutähdehakkeen kustannustekijät ja suurimittakaavainen hankinta. Joensuun yliopisto, metsätieteellinen tiedekunta. Tiedonantoja 131. 107 p. (In Finnish).

Cajander, A.K. 1949. Forest types and their significance. Acta Forestalia Fennica 56. 69 p.

Gustavsen, H.G., Roiko-Jokela, P., Varmola, M. 1988. Kivennäismaiden talousmetsien pysyvät (INKA ja TINKA) kokeet. Suunnitelmat, mittausmenetelmät ja aineistojen rakenteet. Metsäntutkimuslaitoksen Tiedonantoja, 292. 212 p. (In Finnish).

Hakkila, P. 2004. Developing technology for large-scale production of forest chips. Wood Energy Technology Programme 1999–2003. Final Report. Tekes-Technology Programme Report 6/2004. 98 p.

Heikkilä, J., Sirén, M. & Äijälä, O. 2007. Management alternatives of energy wood thinning stands. Biomass and Bioenergy 31: 255–266.

Heinonen, J. 1994. KPL – koealojen puu- ja puustotunnusten laskentaohjelman käyttöohje. Metsäntutkimuslaitoksen tiedonantoja 504. 80 p. (In Finnish).

Huuskonen, S. 2008. The development of young Scots pine stands – precommercial and first commercial thinning. Dissertationes Forestales 62. 61 p. (In Finnish).

— & Ahtikoski, A. 2005. Ensiharvennuksen ajoituksen ja voimakkuuden vaikutus kuivahkon kankaan männiköiden tuotokseen ja tuottoon. Metsätieteen aikakauskirja 2/2005: 99–115. (In Finnish).

Hynynen, J., Härkönen, K., Lilleberg, R., Mielikäinen, K., Repola, J. & Siipilehto, J. 2002. Koivua Suomesta – koivuvarojen kehitysnäkymät. Metsäntutkimuslaitoksen tiedonantoja 840. 53 p. (In Finnish).

— , Ahtikoski, A., Siitonen, J., Sievänen, R. & Liski, J. 2005. Applying the MOTTI simulator to analyse the effects of alternative management schedules on timber and non-timber production. Forest Ecology and Management 207: 5–18.

Hytönen, J. 1994. Effect of cutting season, stump height and harvest damage on coppicing and biomass production of willow and birch. Biomass and Bioenergy 6(5): 349–357.

— & Issakainen, J. 2001. Effect of repeated harvesting on biomass production and sprouting of Betula pubescens. Biomass and Bioenergy 20: 237–245.

— & Kaunisto, S. 1999. Effect of fertilization on the biomass production of coppiced mixed birch and willow stands on a cut-away peatland. Biomass & Bioenergy 17: 455–469.

Hyvän metsänhoidon suositukset. 2001. Metsätalouden kehittämiskeskus Tapio, Helsinki. 95 p. ISSN 1239-6117. (In Finnish).

Hyvän metsänhoidon suositukset. 2006. Metsätalouden kehittämiskeskus Tapio. Metsäkustannus Oy, Helsinki. 100 p. ISSN 1239-6117. (In Finnish).

Hyytiäinen, K. & Tahvonen, O. 2001. The effects of legal limits and recommendations on timber production: the case of Finland. Forest Science 47(4): 443–454.

Jacobson, S., Kukkola, M., Mälkönen, E. & Tveite, B. 2000. Impact of whole-tree harvesting and compensatory fertilization on growth of coniferous thinning stands. Forest Ecology and Management

129: 41–51.

Kaila, S., Kiljunen, N., Miettinen, A. & Valkonen, S. 2006. Effect of timing of precommercial thinning on the consumption of working time in Picea abies stands in Finland. Scandinavian Journal of Forest Research 21: 496–504.

Kärhä, K., Keskinen, S., Liikkanen, R. & Lindroos, J. 2006. Kokopuun korjuu nuorista metsistä. Metsätehon raportti 193. 79 p. (In Finnish).

Karttunen, K. 2006. Energiapuuharvennus osana metsänkasvatusta ja ilmastonmuutoksen hillitsemistä. Helsingin yliopisto, Maatalous-metsätieteellinen tiedekunta, Pro gradu -työ. 85 p. (In Finnish).

Korhonen, K.T., Heikkinen, J., Henttonen, H., Ihalainen, A., Pitkänen, J. & Tuomainen T. 2006. Suomen metsävarat 2004–2005. Metsätieteen aikakauskirja 1B: 183–221. (In Finnish).

Korpilahti, A. 2003. Puupolttoaineen tuotantoketjujen kilpailukyky. In: Kariniemi, A. (ed). Kehittyvä puuhuolto 2003. Seminaarijulkaisu 12.–13.2.2003, Paviljonki, Jyväskylä. p. 73–81. (In Finnish).

Laitila, J., Asikainen, A., Sikanen, L., Korhonen, K.T. & Nuutinen, Y. 2004. Pienpuuhakkeen kustannustekijät ja toimituslogistiikka. Working Papers of the Finnish Forest Research Institute 3. [Online journal]. Available at: http://www.metla.fi/julkaisut/workingpapers/2004/mwp003.htm. (In Finnish).

Mäkinen, H., Hynynen, J. & Isomäki, A. 2005. Intensive management of Scots pine stands in southern Finland: First empirical results and simulated further development. Forest Ecology and Management 215: 37–50.

Metsänhoito- ja perusparannustöiden yksikkökustannukset 2006. 2007. Unit costs of silvicultural and forest-improvement works, 2006. In: Peltola, A. (ed.). Metsätilastollinen vuosikirja 2007. Finnish Statistical Yearbook of Forestry. Metsäntutkimuslaitos. p. 153–186. ISBN 951-40-1985-7.

Mielikäinen, K. 1980. Structure and development of mixed pine and birch stands. Communicationes Instituti Forestalis Fenniae 99(3). 82 p.

— 1985. Effect of an admixture of birch on the structure and development of Norway spruce stands. Communicationes Instituti Forestalis Fenniae 133. 79 p.

— , Hirvelä, H., Härkönen, K. & Malinen, J. 1995. Energiapuu osana metsänkasvatusta Keski-Pohjanmaalla. Metsäntutkimuslaitoksen tiedonantoja 556. 56 p. (In Finnish).

Mustonen, M. 2006. Puukauppa ja hakkuut. Roundwood markets. In: Peltola, A. (ed.). Metsätilastollinen vuosikirja 2005. Finnish Statistical Yearbook of Forestry. Metsäntutkimuslaitos. p. 153–186. ISBN 951-40-1985-7.

Niemistö, P. 2005. Käytännön taimikonhoito. In: Hynynen, J., Valkonen, S. & Rantala, S. (eds.). Tuottava metsänkasvatus. Metsäkustannus Oy, Helsinki. p. 91–96. ISBN 952-5118-72-X. (In Finnish).

Nurmi, J. & Kokko, A. (eds.). 2001. Biomassan tehostetun talteenoton seurannaisvaikutukset metsässä. Metsäntutkimuslaitoksen tiedonantoja 816. 80 p. (In Finnish).

Ojansuu, R. & Henttonen, H. 1983. Estimation of local values of monthly mean temperature, effective temperature sum and precipitation sum from the measurements made by the Finnish Meteorological Office. Silva Fennica 17(2): 143–160.

Olsson, B.A. 1999. Effects of biomass removal in thinnings and compensatory fertilization on exchangeable base cation pools in acid forest soils. Forest Ecology and Management 122: 29–39.

Puukauppa – puun ostot ja hinnat vuosittain. 2006. Metsäntutkimuslaitos. [Internet site]. Available at: http://www.metla.fi/cgi-bin/tilasto/puukauppa/puukauppa.cgi?vv. (In Finnish).

Rosenberg, O. & Jacobson, S. 2004. Effects of repeated slash removal in thinned stands on soil chemistry and understorey vegetation. Silva Fennica 38(2): 133–142.

Ruha, T. & Varmola, M. 1997. Precommercial thinning in naturally regenerated Scots pine stands in northern Finland. Silva Fennica 31(4): 401–415.

Salminen, H., Lehtonen, M. & Hynynen, J. 2005. Reusing legacy FORTRAN in the MOTTI growth and yield simulator. Computers and Electronics in Agriculture 49(1): 103–113.

Salo, M. 2004. Kokemuksia energiapuun korjuusta nuorista metsistä. Nuoret metsät energialähteenä -seminaari. Joensuu, Finland, 31.8.–1.9.2004. 3 p. (In Finnish).

Sauvula, T. 2006. Energiapuun korjuu Etelä-Pohjanmaan hoitamattomissa nuorissa metsissä ja sen vaikutus puuston kehitykseen ja tuottoon. The University of Helsinki. Pro gradu thesis. 62 p. (In Finnish).

Suihkonen, M. 2002. Energiapuu osaksi puuntuotantoketjua. Teho 4/2002: 20–21. (In Finnish).

Tanttu, V., Ahtikoski, A. & Sirén, M. 2004. Korjuuvaihtoehtojen kannattavuus metsänomistajalle nuoren metsän harvennuksessa hankintakaupalla.

Metsätieteen aikakauskirja 4/2004: 509–525. (In Finnish).
Tharakan, P.J., Volk, T.A., Lindsey, C.A., Abrahamson, L.P. & White, E.H. 2005. Evaluating the impact of three incentive programs on the economics of cofiring willow biomass with coal in New York State. Energy Policy 33: 337–347.
Tonteri, T., Hotanen, J.-P. & Kuusipalo, J. 1990. The Finnish forest site type approach: ordination and classification studies of mesic forest sites in southern Finland. Vegetatio 87: 85–98.
Väätäinen, K., Asikainen, A. & Sikanen, L. 2006. Metsäkoneiden siirtokustannusten laskenta ja merkitys puunkorjuun kustannuksissa. Metsätieteen aikakauskirja 3/2006: 391–397. (In Finnish).
Valkonen, S. & Ruuska, J. 2003. Effect of Betula pendula admixture on tree growth and branch diameter in young Pinus sylvestris stands in southern Finland. Scandinavian Journal of Forest Research 18: 416–426.
Valtakunnan metsien inventointi. 2008. [Internet site]. Available at: http://www.metla.fi/metinfo/tilasto/index.htm. (In Finnish).
Valtion tuet yksityismetsätaloudelle. 2006. [Internet site]. Available at: http://www.metsavastaa.net/index.cfm?docID=2979. (In Finnish).
Varmola, M. 1996. Yield and quality of young Scots pine cultivations. Metsäntutkimuslaitoksen tiedonantoja 585.
— & Salminen, H. 2004. Timing and intensity of precommercial thinning in Pinus sylvestris stands. Scandinavian Journal of Forest Research 19: 142–151.
Vuokila, Y. & Väliaho, H. 1980. Viljeltyjen havumetsiköiden kasvatusmallit. Communicationes Instituti Forestalis Fenniae 99(2). 271 p. (In Finnish).
Ylitalo, E. 2006. Puupolttoaineiden käyttö energiantuotannossa 2005. Metsätilastotiedote 820. 8 p. (In Finnish).

Total of 54 references