The Role of Peatlands in Finnish Wood Production – an Analysis Based on Large-scale Forest Scenario Modelling

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Using the Finnish MELA model, a set of scenarios were produced and used to map the possibilities and risks surrounding the utilisation of peatlands in wood production in Finland. One of the scenarios was an estimate of allowable-cut calculated by maximising the net present value of the future revenues using a four per cent interest rate subject to non-decreasing flow of wood, saw logs and net income over a 50-year period, and net present value after the 50 year period greater or equal than in the beginning. The estimate for maximum regionally sustained removal in 1996–2005 was 68 million m^3 per year – approaching 74 million m^3 during the next decades. In this scenario, 14 per cent of all cuttings during the period 1996–2005 would be made on peatlands, which comprise ca. 31 per cent of the total area of forestry land. By the year 2025, the proportion of peatland cuttings would increase to over 20 per cent. The increase in future cutting possibilities on peatlands compensated for a temporary decrease in cuttings and growing stock on mineral soils. The allowable-cut effect was especially pronounced in northern Finland, where peatlands play an important role in wood production. In addition, the sensitivity of cutting possibilities for assumptions related to growth and price were analysed. The estimate of maximum sustainable yield as defined here seems to be fairly robust on the whole, except in northern Finland where the cutting scenarios were sensitive to the changes in the price of birch pulpwood. The proportion of peatland stands that are profitable for timber production depends on the interest rate: the higher the rate of interest the less peatland stands are thinned. The effect of cutting profile on future logging conditions and resulting costs were analysed in two forestry centres. If clear cuttings on mineral soils are to be cut first, an increase in future logging costs is inevitable.

Keywords wood production, peatlands, forest scenario modelling, MELA

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1 Introduction

The total area of forestry land in Finland is 26 million hectares, of which nine million hectares are peatland. Nearly five million hectares have been drained, mostly in the 1960's and 1970's.

From 1950 to 1990 the volume of growing stock increased 22 per cent, even though during the same period the accumulated total drain was higher than the volume of the growing stock in 1990. During that time, the annual volume increment increased by about 27 per cent (Tomppo and Henttonen 1996). This increase was due to investments, cutting profile and silvicultural management, which resulted in changes in the volume of growing stock, the age structure of forests, and the density and structure of stands.

During the same period the annual volume increment on peatlands increased about 80 per cent (Tomppo and Henttonen 1996). That change took place mainly on drained peatlands where the effects of intensified forest management and silviculture were realised in the form of greater volume of growing stock. The main reason for the increase was drainage (Tomppo and Henttonen 1996).

The intensified forest management and improvement in 1950–1990, on the one hand, increased future cutting possibilities and, on the other hand, also via the allowable-cut effect (Kuusela 1959, Schweitzer et al. 1972) allowed an increase in immediate cuttings in mature stands, mainly on mineral soils. Depending on the success of draining and the level of management, drained peatland stands are gradually reaching the commercial size, and thus the maturity, for cutting. However, the increase in wood production potential is not necessarily directly proportional to the increase in growth because sustainable production of wood depends on the volume, growth and structure of forests; and the future production potential is conditional to the forest management practices applied. In addition, the utilisation of cutting possibilities on peatland is affected by accessibility and by the small size of trees, which often results in higher logging costs than on mineral soils.

In terms of wood production, drained peatlands differ from mineral soils with respect to site and stand. Drainage initiates processes in peat soil that lead to improved conditions for root growth with respect to oxygen and nutrient availability. This results in a substantial increase in tree growth after draining. Since ditch systems also deteriorate gradually with time, site conditions may later become worse. Furthermore, on certain sites, peat nutrient stores may not be sufficient. Consequently, significant positive and less predictable negative trends in tree growth can be observed as a function of time elapsed since drainage: a site cannot be regarded as remaining constant over time. It has been shown that tree species, size, age, site factors, and drainage intensity all influence the growth response. Severe impairment of water or nutrient regimes on the site may eventually lead to death of the stand.

In general, peatland stands are characterized by low stocking and slow growth with highly variable size distributions and clumped spatial distribution of trees. On better sites mixed stands are common. After drainage, stands become denser due to regeneration and ingrowth. Great structural variability is, however, observed to persist in peatland stands for decades after drainage.

Risks related to drained peatland stands are mostly due to growth losses resulting from poor drainage conditions. A common management practice on pine mires and the poorest spruce mires is to synchronise maintenance of the ditch network with thinning in order to maintain drainage conditions after the transpiration of trees decreases. According to Hytönen and Aarnio (1998), the profitability of ditch-network maintenance was fairly good even on rather poor sites with low stocking. Usually the best sites and well growing stands do not need maintenance of the ditch network due to the relatively thin peat layer and interception of water by the growing stock.

The Finnish MELA model (Siitonen et al. 1996) was designed in the 1970's to analyse the regional and national level potentials for wood production based on the sample plot and on tree data collected in the National Forest Inventory (NFI). Since the 1980's the Finnish MELA model has been applied in three rounds of national-level forestry analysis: the Forest 2000 Programme (1986), the Revised Forest 2000 Programme (Komiteamietintö 1995:5) and Finland's

National Forest Programme 2010 (1999). For the third round a set of different scenarios was produced (Nuutinen and Salminen 1999). One of the scenarios was an estimate of allowable-cut calculated regionally by maximising the net present value of the future revenues using a four per cent interest rate, subject to non-decreasing flow of wood, saw logs and net income over a 50-year period, and net present value after the 50 year period greater or equal than in the beginning. This estimate of maximum regionally sustained removal for the period 1996–2005 was 67 million m^3 per year – stabilising at the level of about 70 million m^3 for the next few decades. In this scenario, more than ten per cent of cuttings during the period 1996–2005 would occur in peatlands. By the year 2025, the proportion would increase to 30 per cent.

For the third round of the national analysis, the growth models of the MELA model (Ojansuu et al. 1991) were replaced with a new set of models (Hynynen and Ojansuu 1996). The new growth models were expected to produce more accurate growth predictions because they account, for example, for between-tree competition more explicitly than previously. However, the models used to predict tree growth on drained peatlands seemed to overestimate growth in certain types of stands not well covered in sets of modelling data, such as poorest sites or stands in unsatisfactory silvicultural conditions.

In the third round of the Finnish national forestry analysis, maintenance of the ditch network was not defined as a possible human activity, and therefore the costs of thinning peatlands were underestimated even though the estimates of growth implicitly included the effect of ditch-network maintenance. Therefore the net income for the management schedules that included thinning on drained peatland was overestimated.

The aim of this study was to analyse the role of peatland forests in future wood production using the MELA model as a tool for scenario analysis. Three basic scenarios and a set of additional scenarios for sensitivity analysis were designed to map the possibilities and risks around the utilisation of peatlands in wood production. First, the growth models were checked and corrected according to current knowledge; and the growth, management and economic models used in the MELA model were synchronised to correspond to current management practices. Second, based on the calculated scenarios, timber production possibilities and the allowable-cut effect of peatlands were analysed. Third, the effects of different uncertainty factors related to assumptions were studied to give some measures of the number of risks related to possible overestimates. To analyse the sensitivity of scenarios to growth estimates, bias was introduced into the growth models. The sensitivity of scenarios on price relations was studied by changing the price of birch pulpwood. Because there are no direct methods for validating prediction models based on past data, indirect methods were applied to assist decision- and policy makers in evaluating the results. The discussion is extended to relate the results with the assumptions made for the analysis, including the models. In addition, some factors affecting the future utilisation of peatlands in wood production were identified.

Although the simulations cover 50 years, the results are presented mainly for the period 1996–2025. The original data were processed and updated by forestry board districts, but the actual calculations were done separately for each of the forestry centres, which are new administrative units formed, with small adjustments, from forestry board districts. The results are presented mainly for the whole of Finland. The division into southern and northern Finland is used when the results of the sensitivity analysis are interpreted.

2 Material

2.1 The NFI Data

The Finnish Forest Research Institute has surveyed the forests of Finland systematically for more than 70 years. The first NFI was made in 1921–1924. Thereafter, inventories have been carried out with a cycle of about 10 years. This paper is based on data from the 8th NFI (NFI8) from years 1986–1994.

NFI8 data were collected with systematic cluster sampling. The clusters of field plots were located on maps with a systematic grid. In southern Finland the distance between clusters was 7 km in the west-east direction and 8 km in the south-north direction. There were 21 sample plots in each cluster with a distance of 200 m between plots. In northern parts of the country the clusters were smaller, the distance between clusters was wider and the distance between plots was 300 m. In all, 70 500 sample plots were measured. A more detailed description of the sampling design is given by Tomppo et al. (1997).

For each sample plot, several variables were measured at tree and stand levels. The treewise variables were measured for trees selected with a relascope with basal area factor 2 in southern Finland and 1.5 in northern Finland. On average, eight trees were measured on each plot. The variables measured for each selected tree (called a tally tree) include diameter at breast height, tree species, quality class (indicating quality of saw logs) and crown storey class. Every 7th (8th in the northern parts of the country) tree (called a sample tree) was measured in more detail. Variables observed for the sample trees include height, diameter at a height of six meters, thickness of bark, diameter increment, height increment, age, damage, length and wood quality class of each part of the stem.

Variables observed at stand level describe the site, growing stock, accomplished silvicultural and cutting operations as well as recommended silvicultural and cutting operations for the future 10-year period. The description of the site includes, e.g. land use class (forest land, scrub land, waste land, other forestry land, arable land, constructed land etc.), main soil type (mineral soil or peatland), site fertility class, and drainage status as determined by the effect of ditching into the sites. The variables describing the growing stock include, e.g. the number of crown storeys, species composition, mean age, development class, damage, etc.

The land-use class is forest land if the site can produce at least 1 m^3/ha/year of wood with tree species suitable for the site and with a 'normal' management schedule and a rotation age of 100 years. For poorly productive forest (later referred to as scrub land) the estimated productivity is 0.1–1.0 m^3/ha/year. Waste lands produce less than 0.1 m^3/ha/year.

The soil is classified as peatland if the organic layer is peat or if at least 75 per cent of the lesser vegetation is formed of plants typical for peatlands. Peatlands are further divided into three main types: spruce mires, pine mires and treeless mires. The sites are classified into 6 site-type categories according to the vegetation, which indicates the fertility (Huikari 1952, 1974).

Table 1. Area (million ha) by land use class, main soil type and drainage status.

Land use class	Main soil type					
	Spruce mire	Pine mire	Treeless mire	Peatlands total	Mineral soils	Grand total
Forest land						
Undrained	0.50	0.40	0.00	0.90	14.25	15.15
Drained	1.47	2.43	0.00	3.89	1.01	4.90
Total	1.97	2.83	0.00	4.80	15.25	20.05
Scrub land						
Undrained	0.24	1.10	0.00	1.35	0.94	2.29
Drained	0.04	0.65	0.00	0.68	0.00	0.68
Total	0.28	1.75	0.00	2.03	0.94	2.97
Waste land						
Undrained	0.04	0.31	1.64	2.00	1.02	3.02
Drained	0.00	0.04	0.06	0.11	0.00	0.11
Total	0.05	0.36	1.70	2.10	1.02	3.12
Total						
Undrained	0.79	1.82	1.64	4.25	16.20	20.45
Drained	1.51	3.11	0.06	4.68	1.01	5.69
Total	2.29	4.94	1.70	8.93	17.21	26.14

The NFI field team also observes the need for silvicultural measures during the coming 10 year period. These may include, for example, planting, seeding, soil preparation, tending of seedling stands, thinning, clear cutting, cutting for natural regeneration, ditching and/or cleaning of ditches. The silvicultural operations are recommended purely from the standpoint of silviculture and wood production as in guidelines for managing private forests in Finland. The sum of the proposed operations should not, however, be regarded as a recommended 'management plan' for the inventory area.

2.2 Statistics on Peatlands

In Finland, almost 25 per cent (4.80 million ha) of forest land is peatlands, 68 per cent (2.03 million ha) of scrub land is peatland, and the area of drained peatlands is 3.89 million ha on forest land and 0.68 million ha on scrub land (Table 1). In addition, there are 1.01 million ha of ditched forests on mineral soils. Some of this area has previously been peatland, but ditching has changed the original vegetation and peat layer so that the sites are now classified as mineral soils. According to Paavilainen and Tiihonen (1988), about 0.7 million ha of former peatlands are now classified as mineral soils.

Most (52 per cent) of the peatland forests are young thinning stands (Table 2). Advanced thinning stands and mature stands are clearly more frequent on mineral soils than on peatlands.

The area of peatlands drained during the 10-year period preceding the year of field work was 0.37 million ha (Table 3). In addition, ditch cleaning and supplementary ditching have been completed on 0.15 and 0.18 million ha, respectively. Based on the ditch condition in general, i.e. depth, width, and initial ditch spacing, ditch cleaning has been recommended on 0.77 million ha and supplementary ditching on 0.67 million ha. On 0.58 million ha of undrained peatlands ditching would be technically feasible from the standpoint of wood production.

The total volume of growing stock on peatland forests is 377 million m^3 (Table 4). This is 20 per cent of the total volume of growing stock. Peatland forests are less heavily stocked than forests

Table 2. Area (million ha) and proportion (%) of development classes by main soil type.

Main soil type	Open area		Young seedling stands		Advanced seedling stands		Young thinning stands		Advanced thinning stands		Mature stands		Seed tree and shelterwood stands		Total	
	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%	km^2	%
Spruce mires	0.03	1.8	0.10	5.1	0.20	10.0	0.79	40.3	0.58	29.5	0.25	12.7	0.01	0.7	1.97	100.0
Pine mires	0.02	0.6	0.07	2.6	0.52	18.5	1.72	60.8	0.37	13.1	0.11	3.9	0.01	0.5	2.83	100.0
Peatlands total	0.05	1.1	0.17	3.6	0.72	15.0	2.51	52.4	0.95	19.8	0.36	7.5	0.03	0.6	4.80	100.0
Mineral soils	0.25	1.6	1.14	7.5	2.20	14.4	4.48	29.3	3.49	22.9	3.34	21.9	0.36	2.4	15.25	100.0
Grand total	0.30	1.5	1.31	6.6	2.92	14.6	6.99	34.9	4.44	22.1	3.70	18.5	0.39	1.9	20.05	100.0

Table 3. Area (million ha) of accomplished and proposed silvicultural measures and drainage operations on peatlands and mineral soils.

	Tending of seedling stands	Removal of seed trees	First thinning	Other thinning	Clear cutting	Cutting for natural regeneration	New ditching	Cleaning of ditches	Supplementary ditching
Measures accomplished during the past 10-year period									
Mineral soils	1.54	0.37	0.54	1.41	0.93	0.31	0.12	0.12	0.02
Peatlands	0.56	0.06	0.21	0.33	0.12	0.04	0.37	0.15	0.18
Total	2.10	0.43	0.75	1.74	1.05	0.35	0.49	0.27	0.20
Measures proposed for the coming 10-year period									
Mineral soils	1.78	0.53	1.63	1.56	2.16	0.98	0.37	0.06	0.06
Peatlands	0.65	0.10	0.73	0.46	0.28	0.15	0.58	0.77	0.67
Total	2.43	0.62	2.36	2.03	2.44	1.13	0.94	0.82	0.73

on mineral soils. The mean growing stock on peatland forest and scrub land is 55.2 m^3/ha and on forest and scrub land on mineral soils 89.9 m^3/ha. Most (46 per cent) of the growing stock is pine (*Pinus sylvestris* L.). The proportion of spruce (*Picea abies* (L.) Karst.) is 27 per cent and the proportion of birches (mainly *Betula pubescens* Ehrh. and less *Betula pendula* Roth) is 25 per cent.

Thinning has been recommended for 1.17 million ha (Table 3) of the peatland forests in Finland. More than 60 per cent of the thinnings are so-called first thinnings with relatively poor productivity and high logging costs. About 31 per cent of the proposed first thinnings and 27 per cent of all proposed thinnings are on peatland forests. Tending of seedling stands has been proposed for 0.65 mill ha of peatland forests – this is 27 per cent of all proposed tendings of seedling stands. Clear cutting has been proposed on 0.26 million ha, which is only 11 per cent of all clear cutting proposals. Cutting for natural regeneration has been proposed for 0.15 million ha (13 per cent of all cuttings for natural regeneration).

2.3 The MELA Data

The hierarchy of the MELA data consisted of three levels: sample tree level, sample plot level and management unit level. The MELA data included sample plots from forest land, scrub land and waste land. For each NFI8 sample plot the tree data were converted to MELA sample tree variables and the sample plot data to MELA sample plot variables (see Siitonen et al. 1996, p. 263). The MELA sample tree variables included tree species, number of stems per hectare represented by the current sample tree and diameter at breast height. The sample plot variables defined the land area represented by the sample plot, the geographical location of the sample plot, landowner category, land-use category, forest site type, previous treatments and their timing, etc. Especially important variables for peatlands were soil and peatland category, drainage category, feasibility for drainage and year of the last drainage (Siitonen et al. 1996).

Because the sample plots defined with the relascope were not large enough to represent forest stands in the estimation of the stock volume and in defining future treatments, the sample plots were linked with other sample plots that were similar in terms of present stand characteristics and the expected management and development in the future. The grouping was made separately for each sample plot, resulting in as many management units as there were original sample plots. The management unit characteristics were summarised from the sample plots, and the management unit variables were the same as on the sample plot level. The sample plots presented the variation within the management unit.

The management units were classified into three forest management categories: 1) no restrictions for wood production, 2) restrictions for wood production exist, but wood production is

Table 4. Total volume (million m^3) of growing stock and saw log percentage on forest land and scrub land by main soil type and drainage status.

Main soil type and drainage status	Pine		Spruce		Birches		Other broadleaves		Total	
	Volume	Saw log %	Volume	Saw log %	Volume	Saw log %	Volume	Saw log %	Volume	Saw log %
FOREST LAND										
Mineral soils										
Undrained	608.0	43.2	553.3	48.5	155.5	14.8	46.5	5.2	1363.4	40.8
Drained	27.9	34.7	33.3	44.0	16.8	7.3	4.0	4.4	82.1	31.4
Total	635.9	42.8	586.6	48.2	172.3	14.0	50.5	5.1	1445.4	40.3
Spruce mires										
Undrained	7.3	39.3	26.4	34.8	12.0	5.3	1.5	4.5	47.2	27.1
Drained	32.7	37.1	62.0	37.9	53.0	5.4	4.8	4.2	152.6	25.4
Total	39.9	37.5	88.5	37.0	65.0	5.4	6.3	4.3	199.7	25.8
Pine mires										
Undrained	15.3	18.5	2.3	15.0	2.5	1.4	0.1	0.7	20.3	15.9
Drained	99.8	15.7	6.0	12.3	22.5	1.6	0.3	1.5	128.7	13.1
Total	115.1	16.1	8.4	13.1	25.1	1.5	0.5	1.3	149.0	13.5
Total										
Undrained	630.7	42.6	582.1	47.7	170.0	13.9	48.1	5.2	1430.9	40.0
Drained	160.3	23.4	101.4	38.4	92.4	4.8	9.2	4.2	363.2	22.4
Total	791.0	38.7	683.4	46.3	262.3	10.7	57.3	5.0	1794.1	36.4
SCRUB LAND										
Mineral soils										
Undrained	6.7	12.4	2.2	12.7	1.3	1.0	0.2	0.5	10.5	10.8
Drained	0.0		0.0		0.0		0.0		0.0	
Total	6.7	12.4	2.2	12.7	1.3	1.0	0.2	0.5	10.5	10.8
Spruce mires										
Undrained	0.8	10.4	2.1	4.9	2.1	0.4	0.1	0.0	5.0	3.7
Drained	0.1	6.2	0.2	0.0	0.3	0.0	0.0	0.0	0.6	1.3
Total	0.9	9.8	2.3	4.5	2.4	0.4	0.1	0.0	5.7	3.5
Pine mires										
Undrained	13.3	5.6	1.1	0.9	1.1	0.1	0.0	0.0	15.5	4.8
Drained	5.9	1.4	0.2	2.1	0.7	0.0	0.0	0.0	6.8	1.3
Total	19.1	4.3	1.4	1.1	1.8	0.1	0.0	0.0	22.3	3.7
Total										
Undrained	20.7	8.0	5.5	7.2	4.5	0.5	0.3	0.3	31.0	6.7
Drained	6.0	1.5	0.4	1.3	1.0	0.0	0.0	0.0	7.4	1.3
Total	26.7	6.5	5.9	6.8	5.5	0.4	0.4	0.3	38.5	5.6
FOREST AND SCRUB LAND										
Mineral soils										
Undrained	614.8	42.9	555.5	48.3	156.8	14.7	46.7	5.2	1373.8	40.6
Drained	27.9	34.7	33.3	44.0	16.8	7.3	4.0	4.4	82.1	31.4
Total	642.7	42.5	588.9	48.1	173.7	13.9	50.7	5.1	1455.9	40.1
Spruce mires										
Undrained	8.0	36.6	28.5	32.6	14.0	4.6	1.6	4.1	52.2	24.8
Drained	32.8	37.0	62.2	37.8	53.4	5.4	4.8	4.2	153.2	25.3
Total	40.8	36.9	90.7	36.2	67.4	5.2	6.5	4.2	205.4	25.1
Pine mires										
Undrained	28.6	12.5	3.5	10.4	3.6	1.0	0.2	0.6	35.8	11.1
Drained	105.6	14.9	6.3	11.9	23.2	1.5	0.3	1.5	135.5	12.5
Total	134.2	14.4	9.8	11.4	26.8	1.4	0.5	1.2	171.3	12.2
Total										
Undrained	651.4	41.5	587.6	47.3	174.5	13.6	48.5	5.1	1461.9	39.3
Drained	166.3	22.6	101.8	38.2	93.4	4.8	9.2	4.2	370.7	21.9
Total	817.7	37.6	689.3	46.0	267.8	10.5	57.7	5.0	1832.6	35.8

Table 5. Area (million ha) by management categories.

Management category *)	Mineral soil Forest land	Mineral soil Forest land, scrub land and waste land	Peatland Forest land	Peatland Forest land, scrub land and waste land	Total Forest land	Total Forest land, scrub land and waste land
1	13.03	13.03	4.59	4.59	17.63	17.63
2	0.69	1.00	0.07	2.95	0.75	3.95
3	1.53	3.17	0.14	1.39	1.67	4.56
Total	15.25	17.20	4.80	8.93	20.05	26.14

*) 1 – no restrictions for wood production 2 – restrictions for wood production exist, but wood production is not totally forbidden
3 – no wood production is allowed

not totally forbidden and 3) no wood production is allowed. The classification was made with the original NFI8 sample plot variables. The categories were based on the classification of protected areas by the Finnish Environment Institute, and silvicultural guidelines developed for private and state forests. In the first category, thinnings, clear cuttings, seed tree and shelterwood cuttings and removals of seed trees and shelterwood trees were allowed. In the second category, clear cuttings were forbidden. In the third category, no wood production treatments were allowed.

When data are collected over a period of years, the regional analyses may not be comparable with each other. In addition, the results summed to an area larger than the initial districts cannot be linked to a specific year or range of years. Furthermore, there might be more actual changes in forests that affect the results of the wood production analysis in forestry board districts measured in the 1980's than in those measured in the 1990's. These changes may include, for example, the relatively low level of annual cuttings of the early 1990's in Finland, increased areas of non-wood production in northern Finland, etc. To avoid these difficulties, the MELA data were updated to 1996.

The updating consisted of two parts: updating the forest management categories of the management units when necessary and updating the tree and sample plot variables. The update of the forest management categories was based on the data of the Finnish Environment Institute. After the updating, the amount of non-wood production area was 8 per cent of the forest land area and 17 per cent of the area of forest land, scrub land and waste land together (Table 5).

The updating of the tree and sample plot variables was made by the MELA model. The basis of updating was to simulate feasible alternative management schedules for each management unit over a desired update period, and from these simulated management schedules, to select the forestry board district level solution and the corresponding management of the initial management units by linear optimisation.

The simulation, which included both natural processes and human treatments, was made to the beginning of 1996; and the length of the update period varied by management unit, depending on the original inventory year. In the simulation some information about treatments actually made on the sample plots during the update period was used. In the update inventory of NFI8 in 1994, a portion of the original NFI8 sample plots were re-measured. For these sample plots only the actually observed treatments were simulated. Furthermore, satellite images were used to locate sample plots, that had been clear cut during the update period. Satellite images were also used to estimate sample plots, that had not been cut during the update period. For all other sample plots, normal simulation of feasible management schedules was used.

The forestry board district level solution selected by linear optimisation had to fulfil the restrictions related to annual treatments actually made during the update period. These restrictions included number of cubic meters removed by tree species and wood assortments, portions of cutting methods from total cutting areas, areas on which seedling stands were tended, areas of forest drainage, areas of forest fertilisation and removals made by private forest owners. The

Table 6. Estimated total volume (million m^3) of growing stock in 1996 by main soil type and tree species.

	Mineral soil	Peatland	Total
Pine	703.9	198.1	902.0
Spruce	596.7	115.5	712.3
Birch	173.0	104.0	277.0
Other broadleaves	48.4	8.3	56.7
Total	1522.1	425.9	1948.0

area of annual treatments was obtained from the statistics of The Finnish Forest Research Institute. In southern Finland, to ensure the development of the growing stock during updating, the amount of the total growing stock of the update inventory of NFI8 in 1994 was also used.

The resulting forest resource data for 1996 was used as the updated data. The total growing stock on forest land, scrub land and waste land after updating was 1948 million m^3 (Table 6). The growing stock on peatlands was 426 million m^3.

3 Methods

3.1 The MELA Model

The MELA model consists of two parts: an automated stand simulator based on individual trees and the optimisation package based on linear programming, JLP (Lappi 1992). The MELA model automatically simulates a finite number of feasible, i.e. sound and acceptable, alternative management schedules for the stands over the relevant calculation period, and after simulation selects simultaneously both a production programme for the whole forest area and management schedules for the individual stands. Management schedules differ from each other, for example, in timing of management activities.

The simulation of the management schedules for each management unit consists of states and events. The events are natural processes (e.g. ingrowth, growth and mortality of trees) and management activities simulated by the built-in basic event routines of the MELA simulator. In the MELA model version 1996, stand treatment practices include artificial regeneration, clearing of regeneration area, soil preparation, tending of young stands, cuttings, ditching, fertilisation, pruning of pine, and changing the values of management unit variables. The tasks of the basic event routines are to decide the feasibility of the basic events in each state of the management unit, to simulate the details of the basic events (such as logging costs), and to collect the summarised variables. The event parameter of the MELA model makes it possible to define a set of optional events for each simulation application within the built-in event routines and their arguments.

The development of the growing stock is predicted using the sample trees of the sample plots. A set of models based on individual trees that describe natural processes, treatment, management instructions etc. is utilised at the five-year time step. The main simulation variables for trees are the number of stems per hectare, tree species, diameter, height and age. In the MELA model only expected values of the models are used in the simulation. The stochastic variation in natural processes has not been taken into account directly.

3.2 Stand Simulator

3.2.1 Modelling Data

The data selected for simulation models of MELA were obtained by finding the most representative data for development of the models for nationwide use.

Models for mineral soils are based on data collected from the data sets for permanent sample plots INKA (Inventory growth plots) and TINKA (Young forest inventory growth plots) (Gustavsen et al. 1988). These data form a subsample of the stands containing sample plots of the 6th and 7th National Forest Inventories (NFI6, NFI7).

The INKA plots were established during 1976–1982 and were re-measured twice with a five-year interval. TINKA plots were established in 1984–1986 and were re-measured five years after establishment. Additional data for the growth models of birch were obtained from repeatedly measured thinning experiments established by the Finnish Forest Research Institute (Niemistö 1997). Models for self-thinning are based on data collected from untreated control plots of repeatedly measured experimental stands (Hynynen 1993).

The peatland modelling data consisted of two separate data sets: for southern Finland and southern parts of northern Finland, the permanent sample plots (established 1985, re-measured 1990) of the NFI8, and for northern Finland, permanent growth plots of SINKA (Permanent forest inventory growth plots, see Penttilä and Honkanen 1986, Mielikäinen and Gustavsen 1993, Hynynen et al. 1999) were used. The SINKA plots were sampled by stratified systematic sampling from NFI7 sample plots located on peatlands, were established in 1984–1988 and were re-measured five years after establishment. The subsets of NFI8 data and the SINKA data were combined to form one data set for peatland trees.

3.2.2 Prediction of Stand Development

Prediction of stand development was based on individual-tree models. The growth of trees over 1.3 m was predicted with distance-independent models for basal-area growth and height growth of trees. On mineral soils, diameter and height growth were calculated as a function of climate (temperature sum, distance to the sea and to the lakes), site (site index and Cajanders's site type), stand characteristics (e.g. stand density and stage of stand development) and the dimensions of trees (diameter, height, crown ratio, relative size of a tree) as detailed by Hynynen and Ojansuu (1996) and Hynynen et al. (1999).

Juvenile development of trees until they reach the height of 1.3 m, as well as natural regeneration and ingrowth, were predicted with regeneration models. With these models the tree list of a stand was produced for further simulation with individual-tree models.

Mortality of trees was predicted with the individual-tree survival model and stand-level self-thinning model. The probability of a tree surviving was predicted as a function of site, stand density, relative tree size and age of the tree. The self-thinning model controlled stand development in situation, where accelerated mortality is expected due to suppression and competition, for example, in unthinned stands.

Before the models were applied within MELA, they were tested and calibrated against the data from NFI8. The purpose of the calibration was to ensure that the predicted average growth rate is on the level obtained in the growth measurements of the national forest inventory. With the help of calibration, the models were adjusted to be applicable for tree species not included in the modelling data, as well as for the stands growing on extreme sites that were not covered by the modelling data. A detailed description of model calibration is provided by Hynynen et al. (1999).

In the end of the simulation period, information on the level of the management unit for each schedule was updated. Static models were employed to predict stem volume and to assess the technical quality of the stems. Stem volume and wood assortments were stored in a table where the cells are the values predicted with the stem curve models as a function of tree species, diameter and height (Laasasenaho 1982). Management-unit information was then calculated by summing up the treewise information.

3.2.3 Specific Characteristics of Models for Peatlands

A specific set of models was applied for peatlands. In peatland stands, diameter increment for Scots pine, Norway spruce and downy birch (*Betula pubescens*) was predicted with a model for growth of the basal area of a tree (Hökkä et al. 1997, Hynynen et al. 1999). For other broadleaved species, the model for downy birch was used after application of species-specific calibration coefficients derived from the NFI8-data.

In the growth models, the logarithm of basal area growth was explained by tree diameter in the beginning of the five-year growing period. Other tree and stand variables used in the models included the total basal area of trees larger than the target tree, stand basal area, and the proportion of mixed species.

In all models, site was described by the temperature sum and site quality classes (see 2.1). The immediate proximity of the seacoast as expressed by Ojansuu and Henttonen (1983) was also used for birch. Site quality information was coupled into the models using Huikari's (1952, 1974) site classification. Basically, spruce mires were distinguished from pine mires; and within pine mires, different fertility classes were further distinguished by species.

Time since drainage was included in all growth models. The effect of time since drainage was different for each species. In general, stands drained less than 6 years earlier had the lowest level of growth for all species, and the highest growth rate occurred in stands that had been drained 11–25 years earlier. Consequently, the level of growth was adjusted in simulations with respect to the time elapsed since draining.

Another peatland-specific feature included in all models was a categorical stand-level variable indicating the need for ditch network maintenance. In simulations, the value (0/1) of this variable may change over time. A logistic regression model was developed and implemented in version 1999 of the MELA model (Siitonen et al. 1999) to predict the probability of poor condition of the ditch network as a function of time elapsed since drainage and of latitude (Hökkä et al. 2000). In simulations, the probability of poor ditch condition was predicted repeatedly with the model. With a specified probability level (> 0.5), the model suggests when the corresponding dummy variable in the growth models should be used to decrease growth in the predictions. If the ditch network is maintained, the value of the dummy variable should indicate good conditions.

To predict the height of pine, spruce and birch, a static model was applied instead of a height growth model. For other broad-leaved species, the model for birch was applied after the model was calibrated by tree species in the NFI8-data. Tree height was predicted in the beginning of each simulation period, and height growth was then calculated as the difference between tree height at the beginning and end of the five-year simulation period (Hynynen et al. 1999). A more complete description of the modelling work is presented by Hökkä (1997).

The curve for tree height as a function of diameter was specific for each species. This curve was most linear for spruce. Since the average tree height increased as the stand median diameter (D_{gM}) or stand basal area increased, low values for stand attributes resulted in very flat curves, especially for pine and birch, referring to recently drained and sparsely forested mires.

Height curves also became flatter towards the north and for birch, towards higher elevations. Thinning treatment during the past five years increased the intercept for both pine and birch. Scots pine trees on medium sites in Huikari's (1952, 1974) classification system attained slightly greater heights than in other sites.

The number of observations on undrained peatlands was so small that no specific models could be constructed. Subsequently, the same models were used for both drained and undrained peatland stands. For pristine sites, the models were calibrated with the NFI8 data. Since the growth pattern of trees on undrained sites differs considerably from that of trees on drained sites, it is possible that in simulations the stand dynamics will be described incorrectly. To obtain more realistic predictions in pristine peatland stands, some 'rules of thumb' were formulated (Hynynen et al. 1999) and applied to the MELA simulator.

All peatland models were also tested and calibrated against the NFI8 data before they were applied within MELA.

Fertilisation of drained peatlands has been a common management practice during recent decades, and the modelling data also included fertilised stands because it was not possible to omit them. In order to avoid growth predictions that were too high for non-fertilised stands, the effect of fertilisation on growth in the modelling data was estimated as expressed by Hökkä (1997). Growth in non-fertilised stands was estimated to be 0–14 per cent lower than the average in the modelling data.

3.3 Stand Treatment Routines in MELA

3.3.1 Silvicultural Practices

In the MELA model clearing of regeneration area, site preparation, artificial regeneration after clear cutting and tending of a young stand are obligatory silvicultural events as such, but the model is able to choose the timing of these events. Fertilisation, pruning or ditching, except for thinning combined with maintenance of the ditch network, are neither generally used nor in this study were they used in the MELA analyses although they are feasible events for the MELA model.

The costs of silvicultural and forest improvement work were based on time expenditure and unit prices. In this study the deflated (year 1997) average unit prices realised in years 1988–1997 were:

Type of work	Southern Finland	Northern Finland
Cost of clearing the regeneration area, FIM/ha	385	285
Cost of harrowing and scarification, FIM/ha	735	535
Cost of ploughing and mounding, FIM/ha	1090	710
Cost of seeding, FIM/ha	985	870
Cost of pine planting, FIM/seedling	0.50	0.50
Cost of spruce planting, FIM/seedling	0.85	0.85
Cost of birch planting, FIM/seedling	1.15	1.15
Cost of supplementary planting with pine, FIM/seedling	0.85	0.85
Cost of supplementary planting with spruce, FIM/seedling	0.95	0.95
Cost of supplementary planting with birch, FIM/seedling	1.50	1.50
Cost of grass prevention, FIM/ha	525	400
Cost of tending seedling stands, FIM/ha	950	745
Cost of ditch cleaning, FIM/ha	700	550
Unit cost of silvicultural work, FIM/h	80	80

3.3.2 Cuttings

There are six cutting methods available for event definitions: thinning instructions based on basal area, clear cuttings, thinning instructions based on number of stems, removal of over-storey, seed-tree cutting (for natural regeneration of pine, birch and populus) and shelterwood cutting (for natural regeneration of spruce). For example, simulation of thinning based on basal area instructions can be regulated using the parameters thinning intensity, selection of tree size, selection of tree species and minimum cutting removal per hectare.

In general, the same treatment rules apply for mineral soils and peatlands. In this study, all cutting methods, except thinning based on number of stem instructions, were also used for peatlands. Furthermore, in peatland stands the recommended minimum regeneration criterion is mean diameter, while on mineral soils, minimum age is also used. Thinnings on the drained spruce mires of poorer site types and on all pine mires are combined with maintenance of the ditch network. For these drained peatlands, thinning alone was not allowed. The shortest time interval between two successive thinnings/ditch network maintenance events was 20 years. For other thinnings and other cuttings, the shortest time interval was 10 years. Basal area instructions for thinning were given separately for peatland and mineral soil. The values used are recommended by Forestry Centre Tapio (Luonnonläheinen metsänhoito 1994).

The value of the stems was calculated from the wood assortments and unit prices. The prices in the MELA model are constant and exogenous and the capital markets are assumed to be perfect, i.e. money can be saved and borrowed in unlimited quantities at the same price (interest rate). The wood prices used in this study were based on the deflated (year 1997) average realised delivery prices during the 10-year period 1988–1997:

	Saw logs, FIM/m^3			Pulpwood, FIM/m^3		
	Pine	Spruce	Birch	Pine	Spruce	Birch
S Finland	270	226	271	167	191	170
N Finland	247	200	225	173	182	161

The MELA model version 1999 has new models for estimating the logging costs as a function of time expenditure and unit costs. The time-consumption models of Rummukainen et al. (1995) and Kuitto et al. (1994) were implemented. In these models the most important factors affecting time consumption are size of a stem, number of removed stems, harvesting type, the cutting drain and the off-road distance. The unit costs of logging and off-road haulage used here were:

Off-road haulage by forwarders	280 FIM/h
Logging with harvester	420 FIM/h
Manual logging (man with chain saw)	120 FIM/h

In each cutting alternative for a stand, MELA uses the logging practice with the lowest total costs unless the user defines otherwise.

3.4 Optimisation

Hundreds of variables describing the management schedules are produced for the optimisation. The totals of the sample plots and also the management units are obtained as sums of the trees. The variables available in the LP problem and the report writer describe the state and the development of the forests, as well as forest production and its economy over the calculation period. The optimiser simultaneously selects the production program for the whole forestry unit and the corresponding management schedules for sample plots. In the MELA solution the management of forests excluding regeneration stage is endogenous because the simulation of management schedules is based on the models for the development of individual trees, which react to their environment and to changes in their environment caused by man-made treatments.

3.5 The Analysis Design

3.5.1 Basic Scenarios

The wood-production process comprises a set of sequential actions, and the time interval between these actions can be very long. The generally accepted way to handle time in forestry is the net present-value method. In the net present-value calculations all future incomes and costs are discounted to the present. Kilkki (1987) states that the guiding rate of interest should be chosen to correspond to the present forest resources and production goals. In economic terms the production goals depend, for example, on the real rate of interest applied in the capital markets.

In this study three basic scenarios were defined. For the basic scenarios the interest rate of five and four per cent were chosen. The chosen interest rates were higher than that suggested by Kilkki (1987) because of the present forest resources and the effective rate of interest in the capital market.

The first scenario was calculated by maximising without constraints the net present value using a five per cent interest rate. The interest rate of five per cent was chosen to emphasise the time preference for early returns. The second scenario was an estimate of allowable-cut calculated by maximising the net present value of the future revenues using a four per cent interest rate subject to non-decreasing flow of wood, saw logs, and net income over a 50-year period, and net present value after the 50 year period greater or equal than in the beginning. In the second scenario, mineral soils and peatlands belonged to the same domain when sustainability was sought. The third scenario was defined to analyse the allowable-cut effect of peatlands and it was like the second scenario, except that mineral soils and peatlands were in different domains when the level of sustainable production was sought.

In the MELA model the net present values (NPV's) are calculated for each management unit according to Formula 1, and the net present value of the whole forestry unit is the sum of the management units.

$$NPV = \frac{\sum_{t=q}^{T} R_t (1+i)^{T-q} - \sum_{t=q}^{T} C_t (1+i)^{T-q} + LV}{(1+i)^{T-q}} \quad (1)$$

NPV = Present value of future net revenues
t = Time
q = Present time
T = Minimum rotation for a stand after the planning period (50 years) or the maximum time horizon (151 years), whichever is shorter (T is the total simulation period for a stand)
R_t = Revenues at time t
C_t = Cost at time t
i = Interest rate (p/100 per cent)
LV = Value of bare land

Formula 1 is a modification of the classical Faustman formula. The Faustman formula presumes infinite time horizon, and therefore the costs and revenues in the MELA model consist of two components. The first component is the income from cuttings and costs due to silviculture, forest improvement and harvesting during the planning period (50 years in this study). The second component is the revenues and costs beyond the planning period. The development of stands after the planning period is dealt with by proceeding through the simulation with one development alternative (i.e. without branching) for each stand until the stand reaches the regeneration criteria (either the minimum rotation time or the minimum mean diameter before regeneration) or the calculation time exceeds 151 years. In the latter case, the cutting value of the stand is calculated (the value of wood at the roadside minus the costs of clear cutting minus the costs of clearing the regeneration area). The revenues and costs from the rotations after the simulation period are taken into account by the values of bare land (LV).

For the analysis the MELA model was modified to implement both new features of growth models on peatlands such as the model for maintenance of the ditch network, some restrictions on the development of undrained peatland stands, and maintenance of the ditch network whenever pine mires or poorer spruce mires were thinned.

3.5.2 Sensitivity Analysis

Based on the second scenario, two sets of sensitivity analysis were made. The first aimed at studying the effect of possible bias in the growth models of peatlands on the whole system. The MELA model has its own growth calibration system in which the adjustment coefficients of the growth models can be given by tree species and by forestry board districts. The calibration coefficients apply for both diameter and height growth models, and the actual effects on the volume increment should be examined in each individual case. For this study the growth calibration system of the MELA model was adjusted to work separately for mineral soils and peatlands, and for different species and site types. The sensitivity was analysed by calibrating the growth models of peatlands at the lower level. The calibration was five per cent.

The second set aimed at studying the sensitivity of the system to changes in price elements. Birch made up only 25 per cent of the total volume on drained peatlands, but the role of birch could be increasing as the stands gradually mature. However, the future development of an individual stand depends on the applied standwise management practices. The demand for Finnish wood is largely dependent on the world market of forest industry products and substituting raw materials. Because birch has strong substitutes in the pulp industry, the price of birch pulpwood is probably more sensitive than the price of other wood assortments. To decide on management strategies related to birch, forestry analysis of wood-production alternatives and their costs is needed. These alternatives and costs were analysed by setting the unit price of birch pulpwood at the lower level. The decrease was 20 per cent.

4 Results

The annual cutting potential (Scenario 1) that can be harvested according to the present silvicultural recommendations during the years 1996–2005 is about 100 million m^3, of which 15.2 million m^3 is from peatland stands (Fig. 1, Table 7). Cutting potential can be interpreted as the absolute upper limit for the short-term supply of wood. After the first period the cutting potential would decrease to 60 million m^3. The main decrease would occur in stands on mineral soil, where the decline would be nearly fifty per cent. During 1996–2005 the volume of growing stock would drop over 20 per cent, most of it on mineral soils (Fig. 2, Table 8). Removals from peatland stands are fairly constant, indicating that there is not yet much mature wood growing on peatlands. The same conclusion can be made by comparing the growth (Fig. 3, Table 9) with the removals: on mineral soils the cutting potential during the years 1996–2005 exceeds the annual growth by 55 per cent, while on peatlands the removals are 88 per cent of the growth.

Beyond the analysis horizon (year 2026) the cutting potential will start to increase again when the new tree generations on mineral soils have passed the seedling stand stage. During the years 2006–2025 removals from peatland stands will be 25 per cent of the total. By tree species the

Table 7. Cutting potential (million m^3/year) on forest and scrub land by main soil type and tree species excluding non-wood production land according to Scenario 1 in 1996–2025.

	Period 1996–2005	2006–2015	2016–2025
Mineral soil	85.2	46.3	42.3
– Pine	35.0	21.4	21.6
– Spruce	39.8	20.1	15.6
– Birch	8.5	3.7	4.0
– Other broadleaves	2.0	1.0	1.1
Peatland	15.2	14.1	15.0
– Pine	5.7	6.3	7.3
– Spruce	6.0	4.5	3.9
– Birch	3.2	3.1	3.6
– Other broadleaves	0.3	0.2	0.2
Total	100.4	60.4	57.3

Table 8. Total volume (million m^3) of growing stock by main soil type and tree species excluding non-wood production land according to the cutting potential scenario (Scenario 1) in 1996–2026.

	Year 1996	2006	2016	2026
Mineral soil	1385.4	991.6	1014.0	1241.3
– Pine	627.3	506.7	569.9	743.8
– Spruce	561.5	345.3	300.1	331.7
– Birch	151.2	104.3	111.0	137.0
– Other broadleaves	45.3	35.3	32.9	28.9
Peatland	407.1	387.1	373.4	336.1
– Pine	188.9	199.7	202.2	189.5
– Spruce	109.9	89.3	78.0	67.0
– Birch	100.4	91.9	87.3	74.3
– Other broadleaves	8.0	6.2	5.9	5.2
Total	1792.5	1378.7	1387.5	1577.4

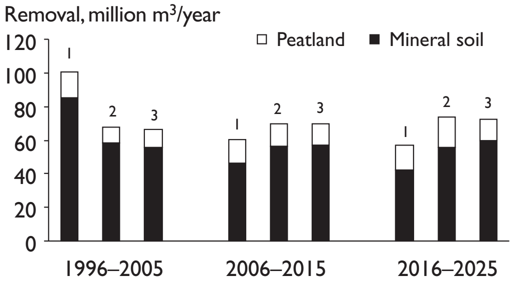

Fig. 1. Removal (million m^3/year) on forest and scrub land by main soil type excluding non-wood production land according to Scenarios 1, 2 and 3 in 1996–2025.

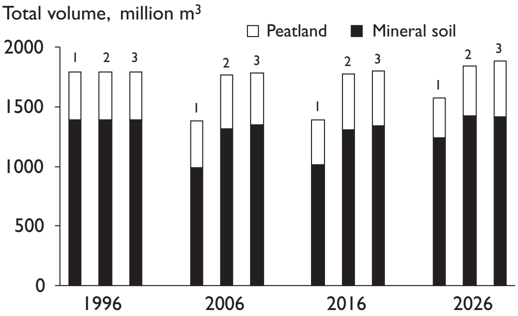

Fig. 2. Total volume (million m^3) of growing stock by main soil types excluding non-wood production land according to Scenarios 1, 2 and 3 in 1996–2026.

proportion varies from 20 per cent (spruce) to 25 (pine) and up to 45 per cent (birch).

According to Scenario 2, the maximum annual sustainable cutting possibility for the years 1996–2005 is 68.0 million m^3, of which 58.3 million m^3 comes from mineral soil stands and 9.7 million m^3 from peatland stands, i.e. 14.3 per cent (Fig. 1, Table 10). The cutting removal of Scenario 2 is 68 per cent of the level obtained in Scenario 1. During the next two decades (2006–2015 and 2016–2025) the sustainable removal will approach the level of 74 million m^3 per year. The increase is due to the increased cutting possibilities on peatlands, because in those periods the removals from mineral soils decrease 3 million m^3. However, the decrease in cuttings and growing stock of mineral soils are only temporary due to the structure of forests. On mineral soils the maximum sustainable removal is close to the growth in 1996–2005 (Fig. 3, Table 12), but on peatlands the removal is only half of the growth. During the next two periods, removal will reach the level of growth on peatlands; and at the same time on mineral soils the growth will exceed removal. The volume of growing stock will be maintained (Fig. 2, Table 11).

Table 9. Average annual increment (million m^3/year) by main soil type and tree species excluding non-wood production land according to the cutting potential scenario (Scenario 1) in 1996–2025.

	Period 1996–2005	 2006–2015	 2016–2025
Mineral soil	54.7	54.4	70.3
– Pine	25.8	29.8	41.2
– Spruce	20.4	16.9	19.7
– Birch	6.3	6.1	8.1
– Other broadleaves	2.2	1.6	1.3
Peatland	17.2	15.3	13.6
– Pine	7.8	7.4	7.0
– Spruce	4.4	3.8	3.1
– Birch	4.6	3.8	3.1
– Other broadleaves	0.4	0.3	0.3
Total	71.9	69.7	83.9

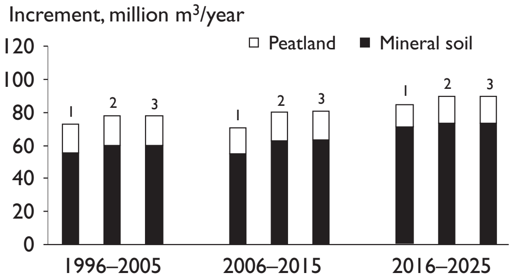

Fig. 3. Average annual increment (million m^3/year) by main soil type excluding non-wood production land according to Scenarios 1, 2 and 3 in 1996–2025.

The proportion of pine removal, including mineral soils and peatlands, will remain nearly the same for three decades, as will the proportion of peatland pine. The proportion of spruce removal and peatland spruce will increase. The reason can be detected in the structure of growing stock where 12.7 per cent of spruce mires are mature but only 3.9 per cent of pine mires are mature.

The definition of sustainability in Scenario 2 concerns only the totals, not the sustainability by tree species or by soil types. In the Scenario 3 the sustainability constraints were applied separately to mineral soils and peatlands in order to study the effect of peatlands on allowable-cut.

Table 10. Maximum sustainable removal (million m^3/year) on forest and scrub land by main soil type and tree species excluding non-wood production land according to Scenario 2 in 1996–2025.

	Period 1996–2005	 2006–2015	 2016–2025
Mineral soil	58.3	56.4	55.8
– Pine	26.9	23.3	24.4
– Spruce	22.5	27.7	25.9
– Birch	7.2	4.3	4.3
– Other broadleaves	1.7	1.2	1.2
Peatland	9.7	13.5	17.9
– Pine	3.5	5.8	8.1
– Spruce	3.6	4.6	5.7
– Birch	2.3	2.9	3.9
– Other broadleaves	0.3	0.2	0.3
Total	68.0	69.9	73.7

Table 11. Total volume (million m^3) of growing stock by main soil type and tree species excluding non-wood production land according to the maximum sustainable removal with sustainable constraints for the whole timber production land (Scenario 2) in 1996–2026.

	Year 1996	 2006	 2016	 2026
Mineral soil	1385.4	1316.1	1308.3	1421.1
– Pine	627.3	603.0	664.9	812.0
– Spruce	561.5	554.7	488.8	448.1
– Birch	151.2	120.1	119.9	131.2
– Other broadleaves	45.3	38.4	34.8	29.8
Peatland	407.1	453.3	465.2	417.8
– Pine	188.9	225.4	241.0	227.5
– Spruce	109.9	118.2	115.2	95.0
– Birch	100.4	102.8	102.4	89.4
– Other broadleaves	8.0	6.9	6.6	6.0
Total	1792.5	1769.5	1773.5	1839.0

The total cutting possibilities do not differ very much between Scenarios 2 and 3 (see Tables 10 and 13, 11 and 14, 12 and 15). However, the effect of peatlands on allowable-cut can be seen in the timing of cuttings. The removals of Scenario 2 during the first period from the mineral soils are five per cent greater and during the

Table 12. Average annual increment (million m^3/year) by main soil type and tree species excluding non-wood production land according to the maximum sustainable removal (Scenario 2) in 1996–2025.

	Period 1996–2005	 2006–2015	 2016–2025
Mineral soil	59.0	62.1	72.9
– Pine	26.9	31.8	41.5
– Spruce	23.3	22.6	23.1
– Birch	6.5	6.1	7.0
– Other broadleaves	2.2	1.6	1.3
Peatland	18.1	17.3	15.7
– Pine	8.1	8.2	7.8
– Spruce	4.8	4.7	4.0
– Birch	4.7	4.1	3.5
– Other broadleaves	0.4	0.4	0.3
Total	77.0	79.4	88.6

Table 13. Maximum sustainable removal (million m^3/year) on forest and scrub land by main soil type and tree species excluding non-wood production land according to Scenario 3 in 1996–2025.

	Period 1996–2005	 2006–2015	 2016–2025
Mineral soil	55.6	56.8	59.6
– Pine	25.8	23.3	25.6
– Spruce	21.1	28.0	28.2
– Birch	7.0	4.4	4.5
– Other broadleaves	1.7	1.2	1.2
Peatland	11.1	12.7	12.8
– Pine	4.1	5.7	5.9
– Spruce	4.2	3.9	3.8
– Birch	2.5	2.8	2.9
– Other broadleaves	0.3	0.2	0.2
Total	66.7	69.5	72.3

Table 14. Total volume (million m^3) of growing stock by main soil type and tree species excluding non-wood production land according to the maximum sustainable removal with sustainable constraints (Scenario 3) in 1996–2026.

	Year 1996	 2006	 2016	 2026
Mineral soil	1385.4	1347.5	1342.3	1415.3
– Pine	627.3	615.9	680.2	813.6
– Spruce	561.5	570.6	505.4	442.3
– Birch	151.2	122.0	121.5	129.9
– Other broadleaves	45.3	39.0	35.2	29.5
Peatland	407.1	436.2	454.0	465.4
– Pine	188.9	217.9	231.7	242.9
– Spruce	109.9	111.1	114.6	116.5
– Birch	100.4	100.3	101.0	99.4
– Other broadleaves	8.0	6.9	6.7	6.5
Total	1792.5	1783.7	1796.2	1880.6

Table 15. Average annual increment (million m^3/year) by main soil type and tree species excluding non-wood production land according to the maximum sustainable removal with sustainable constraints (Scenario 3) in 1996–2025.

	Period 1996–2005	 2006–2015	 2016–2025
Mineral soil	59.3	62.8	72.9
– Pine	27.1	32.1	41.5
– Spruce	23.5	23.0	23.2
– Birch	6.5	6.1	7.0
– Other broadleaves	2.2	1.6	1.3
Peatland	17.9	17.0	16.1
– Pine	8.0	8.0	7.9
– Spruce	4.7	4.6	4.3
– Birch	4.7	4.1	3.6
– Other broadleaves	0.4	0.4	0.3
Total	77.2	79.8	89.0

third period seven per cent smaller than those of Scenario 3 in which, correspondingly, the cuttings from peatlands during the first period are 15 per cent greater but during the third period (2016–2025) 20–30 per cent smaller. In northern Finland the allowable-cut effect is more prominent than in southern Finland. This is quite obvious because peatlands play a greater role in northern Finland than in southern Finland. In northern Finland 35 per cent of the growing stock, 30 per cent of the growth and 25 per cent of removals originate from peatland stands, while these figures for southern Finland are 18, 15 and 16 per cent, respectively.

The sensitivity of cutting possibilities was studied by decreasing the growth of peatlands by five per cent and by decreasing the delivery price of birch pulpwood by 20 per cent. The reduction of growth did not affect the total cutting possibilities much, because in all scenarios the effect was, more or less, one per cent. The cutting removal of the first period even increased to some extent, because it became unprofitable to grow some of the peatland stands further. Of course, the effects were stronger on peatlands where the cutting possibilities decreased 3–6 per cent during the analysis horizon and beyond that still more (6–10 per cent) due to the compound growth. These results were very similar in southern and northern Finland.

The 20 per cent reduction in the price of birch pulpwood had even less effect on the total cutting possibilities. This is probably due to the formulation of LP problem, where there are no constraints on maximum removals, i.e. due to the positive net present value, all cuttings are, in principle, feasible. Naturally the effects are clearer for birch and other broadleaves, for which the reduction of cutting removals was 2–4 per cent on mineral soils and 10 per cent on peatlands. These numbers almost doubled in northern Finland and thus there is quite a marked difference between southern and northern Finland.

On one hand, in southern Finland cutting of mineral soil stands is focused more on birch and other broadleaved alternatives than in the base scenarios because the reduction of price has diminished the profitability of growing mature broad-leaved trees; and consequently the growing stock of deciduous trees decreases compared to that of coniferous trees. On the other hand, in northern Finland the cuttings of birch and other broadleaves are smaller than in the base scenarios; and growing stock and growth of deciduous species increase during the calculation horizon, but beyond that the removals increase again. In northern Finland the less mature trees are probably allowed to grow further in order to compensate for the reduction of price and to make later cuttings more profitable.

The proportion of peatland stands that is profitable for timber production depends, for example, on the interest rate. The higher the interest rate the less peatland stands are thinned – even if the total harvest increases. When the rate of interest used in Scenario 2 changes from 2 to 4 per cent, maintenance of the ditch network is decreased by 50 per cent.

The results of Scenarios 1 and 2 were analysed in more detail at two forestry centres, namely Pohjois-Savo and Pohjois-Pohjanmaa (Table 16). Because in the MELA model the management of forests is endogeneous, variables such as mean annual increment (m^3/ha/year) will indicate the development of forest resources according to the cutting programme implemented in the particular scenario. In Pohjois-Savo the mean annual increment on peatlands in 1996–2005 in both scenarios is close to the mean annual increment on mineral soils. This indicates that many mature peatland forests in Savo are growing on fertile sites. During 2006–2025 the difference between peatlands and mineral soils becomes distinct: in both scenarios the mean annual growth on peatlands is decreasing, on average, by 1 m^3/ha/year when the less fertile sites are allowed to grow. At the same time, on mineral soils the mean annual increment is increasing by more than 1 m^3/ha/year.

In both scenarios the mean annual growth on mineral soils in Pohjois-Pohjanmaa is, in general, less than the corresponding growth on peatlands in Pohjois-Savo. The difference in mean annual increment between peatlands and mineral soils in Pohjois-Pohjanmaa is nearly 1 m^3/ha/year already during 1996–2005, but the increase in mean annual growth on mineral soils and the decrease on peatlands during later periods is considerably smaller than in Pohjois-Savo.

In the MELA model the removal and logging costs are calculated as a function of conditions of management units at the time of the operation. Therefore variables such as average removal from cuttings and average logging costs indicate the conditions of logging according to the particular scenario over the planning period. In Pohjois-Savo the average removal in 1996–2005 on mineral soils in Scenario 1 is 30 m^3/ha more than in Scenario 2; but when the average removal in Scenario 2 decreases only 10 m^3/ha during 2006–2025, in Scenario 1 the average removal drops by nearly 70 m^3/ha. The change is almost directly related to the decrease in average removals caused by regeneration cutting (58 m^3/ha). On peatlands the difference between Scenarios 1 and 2 is smaller. In Scenario 1 the

Table 16. Mean annual growth (m^3/ha/year), average removal from cuttings (m^3/ha) and average logging costs (mk/m^3) by main soil types according to the cutting potential (Scenario 1) and the maximum sustainable removal (Scenario 2) in two forestry board centres (Pohjois-Savo and Pohjois-Pohjanmaa).

	Scenario 1			Scenario 2		
	1996–2005	2006–2015	2016–2025	1996–2005	2006–2015	2016–2025
POHJOIS-SAVO						
Mineral soil						
– Mean annual growth	4.5	4.6	6.2	4.9	5.3	6.3
– Average removal	165	97	97	135	125	127
– Average logging costs	46	57	60	48	49	52
Peatland						
– Mean annual growth	4.2	3.6	2.9	4.5	4.2	3.5
– Average removal	118	94	101	99	102	117
– Average logging costs	60	63	61	61	60	57
POHJOIS-POHJANMAA						
Mineral soil						
– Mean annual growth	2.6	2.5	3	2.8	2.8	3.2
– Average removal	105	64	66	98	73	74
– Average logging costs	60	64	67	60	61	61
Peatland						
– Mean annual growth	1.8	1.7	1.5	1.9	1.8	1.7
– Average removal	87	72	76	80	76	80
– Average logging costs	74	73	73	76	72	68

average removal on peatlands in 2006–2025 is at nearly the same level as that on mineral soils.

In Pohjois-Pohjanmaa the average removal from mineral soils in 1996–2005 is at the same level as that on peatlands in Pohjois-Savo, but in 2006–2025 is considerably lower, even lower than on peatlands in Pohjois-Pohjanmaa during the same period.

In Pohjois-Savo in 1996–2025 the average logging costs in Scenario 2 remain around 50 FIM/m^3; but in Scenario 1 the costs will increase to 60 FIM/m^3 in 2016–2025, which is close to the level on peatlands and mineral soils in Pohjois-Pohjanmaa. The average logging costs in Pohjois-Pohjanmaa are, in general, 10 FIM/m^3 higher than in Pohjois-Savo. In Scenario 2 the logging costs on peatlands will decrease from 76 FIM/m^3 in 1996–2005 to 68 FIM/m^3 in 2016–2025, mainly because the average removal in regeneration cutting increases from 109 m^3/ha to 136 m^3/ha.

5 Discussion

5.1 Evaluation of the Models and Assumptions behind the Analyses

The scenarios are not defined to predict the future but rather to analyse dependencies between management actions and future development. The usefulness of the scenarios and the success of decisions based on them depend on the assumptions – as well as the models – selected for the analysis. Predicting the development of forest resources is complicated due to the number and complexity of the relevant factors and to imperfect knowledge of their dynamics and interactions (Siitonen 1993).

The peatland modelling data are somewhat unbalanced with respect to regionality and are clearly unbalanced with respect to tree size. Because of the concentration of practical forest drainage in the 1960s and 1970s, most stands in the sample were composed of trees that were, on average, small. Thus there were problems in model construction when the growth or height of large trees was predicted.

The self-thinning models derived for even-aged stands growing on mineral soil sites may be incapable of predicting self-thinning in drained peatland stands, which are characterised by uneven size-distribution and clumped spatial distribution of trees. Furthermore, it is probable that on drained peatlands self-thinning, or mortality, is to some extent a function of site drainage, which, in turn, is of no importance in models derived for mineral soil sites.

The analysis presented here was based on updated NFI data. The resulting initial MELA data include uncertainty about the structure of forests because the cutting statistics used to locate the cuttings do not contain information for cuttings on peatland, and therefore the proportion of cuttings on peatland and mineral soils may in reality be different from that used in the updating process.

When the initial MELA data were updated to the year 1996, the estimates of the height of the dominant trees at the age of 50 years were calibrated using information for the MELA sample trees. The calibration was not repeated in the simulation of management schedules. It might be useful to save the information on the calibrated estimates of the height of the dominant trees at the age of 50 years in the updated initial MELA data file to be used in the simulation.

The use of NFI data puts some restrictions on the analysis. The NFI sample-plot data do not include information on haulage distance or logging conditions, and therefore the default value had to be used. The default value of haulage distance is derived from statistics which may not represent the future situation.

In practice, the effect of haulage distance can be taken into account by synchronising logging units in time and space. To analyse the effects of synchronisation, multi-source inventory data are needed in order to take spatial relationships into account. The multi-source inventory data would also facilitate analysis of the environmental impact of logging operations.

In the analysis it is assumed that the current technology can also be applied in the future. New machinery specialised for peatland conditions is, however, being developed and the productivity and environmental friendliness of these machines may be better than that of most machinery used at present.

The statistical models widely applied in forestry scenario analysis are based on past observations, and therefore their use is justified only when the external conditions remain fairly stable. In the MELA model, forest management is assumed to be intensive with regard to artificial regeneration and tending of young stands because the models of natural processes, especially in young stands, cannot forecast the effects of extensive management. Therefore the treatments related to regeneration stage are set as obligatory and those treatments are not solved endogeneously.

In the MELA model maintenance of the ditch network synchronised with thinning of peatlands is a treatment option which makes it possible to determine endogeneously the amount of peatland stands that are profitable for timber production. When the costs of maintaining ditch network together with the costs of logging are subtracted from the revenues, the higher the rate of interest (see Formula 1) is the less profitable thinning of peatland stands becomes.

In general, the same management rules were assumed to apply for both mineral soils and peatlands. There is little experience of regeneration on peatlands, and forecasting the development of the second generation is even more uncertain than forecasting of the first. When more experience is gained, it is possible that new regeneration methods for peatlands will be developed.

The same requirement for minimum amount of timber removed by thinning was used for mineral soils and peatlands. Due to the probability of overestimating the growth of the stands on drained peatlands and the resulting overestimate of later stand volumes, the probability of simulating unnecessary or unprofitable thinning increases.

The same volume tables and price lists apply for both mineral soils and peatlands. Thus, the possible differences in the stem form or factors related to wood quality or the ability of the forest industry to pay cannot be taken into account in the economic analysis. The modelling approach based on individual trees, however, makes it possible to incorporate models that predict the quality factors and their development whenever these models are available.

5.2 Evaluation of the Results

According to the definition applied, Scenario 1 should be close to the proposed measures of NFI, i.e. the amount of wood that could be harvested annually if silvicultural recommendations are applied. The area of clear cutting in Scenario 1 is nearly the same as in NFI, but Scenario 1 suggests less thinning than the NFI reports. This may be the result of the optimisation problem where the requirement for return was set at five per cent. The NFI field team recommends operations mainly from the standpoint of silviculture and no requirement for economic returns are set.

According to Scenario 1, the immediate cutting potential is mainly on mineral soils and later increasingly on peatlands. If the clear cuttings are ranked to be cut first, it is inevitable that logging costs will increase in future.

Scenario 2 shows the maximum level of cutting that can be sustained also in the future. In Scenario 2 the quantity of first thinnings is close to the level of accomplished first thinnings recorded in NFI. As defined in the optimisation problem, the wood production programme takes into account the sustainability of the net income that will also keep logging conditions fairly stable in the future.

According to maximum sustainable yield, the increase of cuttings in the following decades on peatlands allow an immediate temporal increase in cuttings on mineral soils, but there is not as profound an allowable-cut effect as was detected during the third round of national-level forestry analysis (Nuutinen and Salminen 1999). This is mainly due to the changed growth models for trees growing on peatlands. In the previous calculation the growth of peatland stands was for several decades 20–30 per cent of the total growth. In the present results the growth of peatland stands is only slightly above 20 per cent of the total growth. The allowable-cut effect was, however, detected via timing of cuttings and was especially pronounced in northern Finland, where peatlands seem to play an important role in wood production.

When the sensitivity of cutting possibilities for assumptions related to growth and price were analysed, the estimate of maximum sustainable yield, as defined here, seems to be fairly robust on the whole, except in northern Finland where the cutting scenarios were quite sensitive to changes in the price of birch pulpwood.

Due to the number of possible schedules for each stand, the number of possible futures of the forest resource is nearly infinite, within the limits of the structure of forests. The most probable development of forest resources is dependent on the public forest policy and the pattern of human behaviour as a whole. A precondition for forecasting forest use is to predict human activities, e.g. cutting behaviour and management practices, as a consequence of the changing social and economic situation. The absence of quantitative consideration of future needs and potentials may result in adopting management practices that contradict the actual goals. To maintain sufficient or sustainable forest production in the future by regulating management practices, the explicit long-term goals of forestry or options that the present generation wants to maintain for the future should be defined. The choice of goals and options can be supported by careful analysis of the alternatives and their costs.

The utilisation of peatlands will be decided in the market where wood producers and wood users negotiate and make decisions. In the MELA model the standing value of wood is calculated by extracting the logging costs from the roadside price. In the analysis the possible gap between the stumpage-price expectations of forest owners and the price derived from the roadside price is not taken into account. If the short-term balance in the wood market leads to a wood procurement strategy like Scenario 1 where the best stands are cut first, there are two possible futures. In the first one, the use of wood remains at the current- or a higher level, and wood users and wood producers will agree on the price at which those stands where logging costs are considerably higher than at the present can be kept in wood production. New technological innovations or intensified silviculture can be used to decrease logging costs. In the second possibility, some of the peatland forests will become noncommercial and may be left outside of wood production because it is not technically or economically feasible to cut them. If all or some of the forests growing on peatland are left outside of wood production, the decreasing effect on maximum sustainable yield may be greater than the amount of wood produced in those forests that remain outside.

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