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Mikko T. Niemi[1,2], Marjo Palviainen[1] and Annamari Laurén[1]

Enhanced multi-objective decision support in peatland forestry using Peatland simulator SUSI

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Highlights

- Reaching multidimensional economic and environmental objectives in peatland forest management can be enhanced using process-based ecosystem models.
- Applying ditch depth of 60 cm in ditch network maintenance improved the trade-off between timber production and soil greenhouse gas emissions compared with the conventional ditch depth of 90 cm.
- Intensive drainage can reduce tree growth in southern Finland during dry summers.

Abstract

Boreal peatland forests have been extensively drained to increase timber production, but the maintenance of shallowed ditches has been questioned due to increased greenhouse gas (GHG) emissions and negative impacts on water quality. Ditch network maintenance (DNM) lowers water table, which typically increases tree growth, but also increases rate of peat decomposition and consequently CO_2 emissions. Multi-objective forest planning balances between the conflicting economic gains and adverse environmental impacts. We used a process-based Peatland simulator SUSI to simulate three management scenarios for 20 forest stands, covering the variety of growing conditions in Finland. We studied how DNM with a reduced ditch depth (60 cm) and a conventional ditch depth (90 cm) affected stand growth, GHG balance, and nitrogen and phosphorus export. Over a 20-year simulation period, annual volume growth response was on average 0.8 m^3 ha^{-1} when ditch depth was changed from 30 cm to 60 cm and 1.0 m^3 ha^{-1} when ditch depth was changed from 30 cm to 90 cm. In southern Finland, DNM decreased stand growth in fertile sites. Soil GHG emissions increased on average by 49% and 119% in 60 cm and 90 cm ditch depths, respectively, compared to 30 cm ditch depth. The cost of reducing GHG emissions ranged from 0–22 € per ton of CO_2 in our study sites and scenarios. Our results support the idea that omitting DNM or reducing ditch depth may lead to acceptable compromises, as the marginal cost of soil GHG emissions considerably increases with increasing ditch depth.

Keywords ditch depth; drainage; forest planning; greenhouse gas emissions; nutrient leaching; trade-offs; tree growth

Addresses [1]Department of Forest Sciences, University of Helsinki, 00014 Helsinki, Finland; [2]School of Forest Sciences, University of Eastern Finland, 80101 Joensuu, Finland
E-mail mikko.t.niemi@helsinki.fi

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1 Introduction

In boreal peatland forests, drainage has been considered a prerequisite for economically productive tree growth (Heikurainen 1964; Sarkkola et al. 2012), and consequently peatlands have been extensively drained to increase timber production throughout the boreal region, especially in Finland (Päivänen and Hånell 2012). The condition of ditches tends to deteriorate over time due to erosion, sedimentation, and vegetation encroachment (Saarinen 1935; Stenberg 2016), resulting in reduced ditch water transport. This leads to higher ditch water levels, decreased drainage and higher water table (WT) in the forest. Typically, high WT in peat reduces tree growth (Heikurainen 1980). Therefore, ditch network maintenance (DNM, i.e. cleaning old ditches and/or adding ditches) has been a recommended forest management practice in Finland (Vanhatalo et al. 2019). The 13th National Forest Inventory (NFI13) proposed DNM for 0.8 million ha of productive (annual growth greater than 1 m^3 ha^{-1} a^{-1}) forestry-drained peatlands, representing 18% of total drained peatland forests (Korhonen et al. 2024). In the NFI, the need for DNM was assessed as a combined effect of site fertility, temperature sum, stand volume, and visual observation of ditch condition, tree growth, and soil wetness (Korhonen 2023).

The feasibility of peatland drainage have been questioned due to increased greenhouse gas (GHG) emissions (Ojanen et al. 2010; Jauhiainen et al. 2019) and the export of sediments, nutrients, and organic carbon that cause eutrophication, turbidity, and browning of water bodies (Nieminen et al. 2017; Finér et al. 2021; Koivunen et al. 2023). Timber production may conflict with other ecosystem services such as climate change mitigation, clean water provision, biodiversity, and recreational benefits. Thus forest planning seeks an acceptable balance between the harvest revenues and the environmental impacts to promote sustainable peatland forestry (Miettinen et al. 2020; Eyvindson et al. 2023; Ahtikoski et al. 2024). Too intensive drainage should be avoided because late summer WT of approximately 35 cm below the soil surface is sufficient for near-maximal tree growth (Sarkkola et al. 2012), and deeper WT causes negative environmental impacts (Hökkä et al. 2021). Recent findings indicate that deeper WT has decreased tree growth in transformed drained peatlands, where the development of a mor humus layer has altered nutrient cycling and site hydrology (Hökkä et al. 2025). In the future, global warming will expose boreal forests to increasingly frequent droughts (Ruosteenoja and Jylhä 2021), making peatland forests vulnerable to over-drainage and decreased tree growth. The need for water management should shift forest planning from stand-level drainage decisions to catchment-level planning.

In forested peatlands, timber production and other ecosystem services depend on tree species, site fertility, climate, and ditch depth (Ojanen et al. 2010; Sarkkola et al. 2012; Nieminen et al. 2017; Tong et al. 2024). Forestry decision support systems based on simulation and optimization methods (Rasinmäki et al. 2009; Lämås et al. 2023) have enabled the search for optimized forest management alternatives with respect to multiple decision criteria. However, this approach has primarily been applied in mineral soils, and the connected empirical growth models cannot fully account for the wide range of hydrological conditions that depend on drainage, peat properties and weather. Decision support in forest management can be improved by integrating process-based ecosystem models to the planning. The advantage of process-based ecosystem models is that they can be used to simulate complex ecosystem interactions according to causal or mechanistic principles (Mäkelä et al. 2000; Gilson et al. 2025). Novel, advanced process-based Peatland simulator SUSI (Laurén et al. 2021; Palviainen et al. 2024) enables multi-objective forest management planning also in peatlands. SUSI is suitable for studying the economic and environmental objectives with respect to drainage intensity or forest management practices in different site types and climatic conditions. This is because it simultaneously calculates WT, water, nutrient and carbon fluxes and balances, biomass growth, and nutrient export to ditches. A further advantage of SUSI is that it uses standard forest inventory and site data as input.

Drainage intensity affects wood production, ecosystem and soil carbon balances and nutrient exports to water courses (Saari et al. 2025). Optimal drainage intensity may vary depending on site type, weather conditions and according to objectives. Holistic understanding of drainage intensity considering wood production, economy and environmental impacts is lacking.

The aim of this study was to investigate the effect of ditch depth on stand growth, forest value, GHG balances and nutrient export to watercourses using nationally representative forest data in different site types. We used the Peatland simulator SUSI (Laurén et al. 2021; Palviainen et al. 2024) to simulate three ditch depth scenarios (30, 60 and 90 cm) for 20 drained peatland forest stands. The stands represented different site fertility classes (SFC) and average stand characteristics in four regions of Finland. Additionally, we evaluated the potential application of ecosystem models in forest management decision-making processes.

2 Material and methods

2.1 Forest data

We divided Finland into four study regions: southern Finland (SF), central Finland (CF), North Ostrobothnia–Kainuu (NOB–K) and Lapland, covering the range of climatic conditions within mainland Finland (Fig. 1). In all regions, we examined the four most common SFCs of transformed drained peatlands identified by Vasander and Laine (2008) (Fig. 2). In decreasing order of soil fertility, these are herb-rich heath (Rhtkg), bilberry (*Vaccinium myrtillus* L.) type (Mtkg), lingonberry (*Vaccinium vitis-idaea* L.) type (Ptkg), and dwarf shrub type (Vtkg). Together, these SFCs cover 98% of the productive forestry-drained peatlands in Finland (Natural Resources Institute Finland 2023).

We calculated the representative forest attribute data for the SFC and region-specific simulations using a two-step procedure, as shown in Fig. 2. First, we used the NFI computing service (Natural Resources Institute Finland 2023) to determine the arithmetic mean stand volume for the four SFCs in each region (Table 1). Second, we searched openly available inventory plots from the Finnish Forest Centre (FFC 2023) for those thinning-stage and mature peatland forests where the stand volume was within 10 m^3 ha^{-1} of the NFI-derived mean stand volume. These plots were used to derive forest attributes of stem number, basal area, mean diameter, mean height, dominant height, and total and assortment volume for each region-specific SFC (Table 2). In addition, the selection was limited by dominant tree species, as shown in Fig. 2, because Scots pine (*Pinus sylvestris* L.) is the only commercial tree species on Ptkg and Vatkg sites, while Norway spruce (*Picea abies* (L.) Karst.) is the only economically viable tree species on Rhtkg.

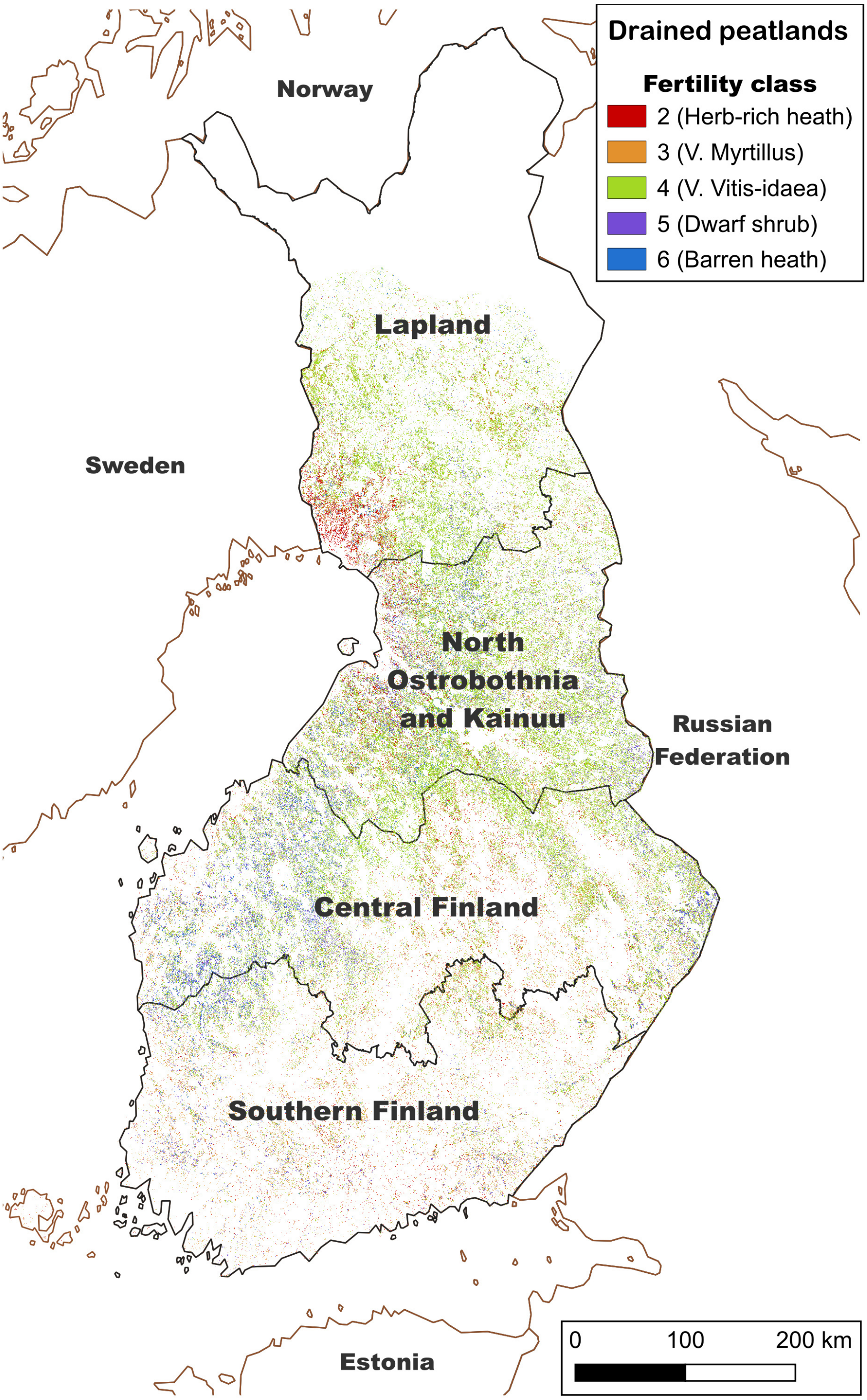
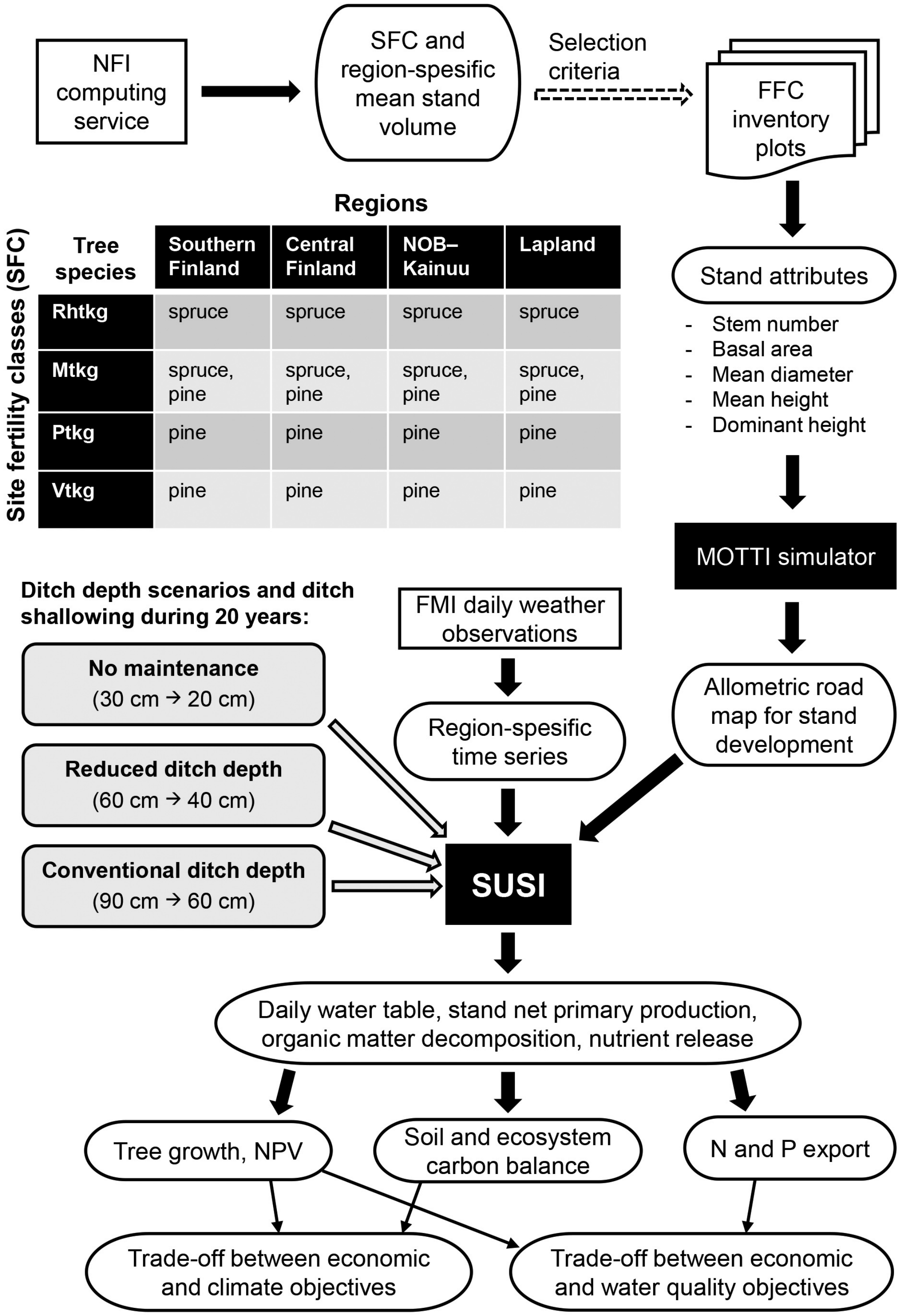


Fig. 1. Study regions and presence of productive (annual growth greater than 1 m^3 ha^{-1} yr^{-1}) drained peatland forests classified by fertility class. Administrative boundaries from the National Land Survey of Finland, 4/2024. Peatland fertility map: Geological Survey of Finland (GTK) (2024) open license CC BY 4.0, including GTK's data of peatland fertility levels in Finland 1.0/2023, imported from the Hakku service on July 31, 2024.



Site fertility classes (SFC)	Regions			
Tree species	Southern Finland	Central Finland	NOB–Kainuu	Lapland
Rhtkg	spruce	spruce	spruce	spruce
Mtkg	spruce, pine	spruce, pine	spruce, pine	spruce, pine
Ptkg	pine	pine	pine	pine
Vtkg	pine	pine	pine	pine

Fig. 2. Study procedure. First, the representative forest attribute data were derived from the Finnish Forest Centre (FFC) inventory plots for 20 forest stands, as shown in the table. Details of the allometric roadmap processed by the MOTTI simulator can be found in Laurén et al. (2021), section 2.3.8. Three ditch depth scenarios were simulated for all study sites. SUSI calculates daily hydrological and biogeochemical fluxes of the ecosystem, which are derived into economic and environmental indicators and their trade-offs.

Table 1. Total area, area of productive (annual growth greater than 1 m^3 ha^{-1} yr^{-1}) peatland forests and mean volume of productive peatland forests of different site fertility classes (SFC) in different regions. SFCs were classified according to Vasander and Laine (2008). Data derived from the NFI computing service (Natural Resources Institute Finland 2023).

Region	SFC	Abbreviation	Total area [ha]	Productive forests [ha]	Mean volume [m^3 ha^{-1}]
Southern Finland (SF)	Herb-rich heath	Rhtkg	151 255	145 041	177
	Vaccinium myrtillus	Mtkg	313 263	299 173	168
	V. vitis-idaea	Ptkg	204 703	194 034	135
	Dwarf shrub	Vtkg	121 811	95 130	95
Central Finland (CF)	Herb-rich heath	Rhtkg	149 554	139 549	153
	V. myrtillus	Mtkg	445 609	415 501	146
	V. vitis-idaea	Ptkg	521 154	467 359	122
	Dwarf shrub	Vtkg	371 867	243 159	83
North Ostrobothnia–Kainuu (NOB–K)	Herb-rich heath	Rhtkg	106 670	80 914	116
	V. myrtillus	Mtkg	372 538	264 537	130
	V. vitis-idaea	Ptkg	669 930	401 992	107
	Dwarf shrub	Vtkg	378 863	157 673	71
Lapland	Herb-rich heath	Rhtkg	63 870	45 495	90
	V. myrtillus	Mtkg	121 036	80 652	119
	V. vitis-idaea	Ptkg	369 941	197 602	81
	Dwarf shrub	Vtkg	213 000	45 371	52

Table 2. Forest attributes representing average forest characteristics in different regions and site fertility classes (SFC), calculated from Finnish Forest Centre inventory plots (FFC 2023). SF = Southern Finland, CF = Central Finland, NOB–K = North Ostrobothnia–Kainuu, N = number of stems, BA = basal area, D_g = basal area-weighted mean diameter, H_g = basal area-weighted mean height, H_{dom} = dominant height, VOL = stem volume. SFCs were classified according to Vasander and Laine (2008). The * indicates the extended range of selection by stand volume due to lack of similar field plots.

Region	SFC and dominant tree species	FFC plots	N [ha^{-1}]	BA [m^2 ha^{-1}]	D_g [cm]	H_g [m]	H_{dom} [m]	VOL [m^3 ha^{-1}]
SF	Rhtkg (spruce)	6	1073	22.6	20.3	16.4	19.2	178
	Mtkg (spruce)	14	851	20.2	21.3	17.4	19.7	169
	Mtkg (pine)	16	932	19.8	22.0	17.9	20.2	168
	Ptkg (pine)	44	915	16.8	20.2	16.6	18.6	134
	Vtkg (pine)	11	1156	15.1	15.0	12.3	14.4	94
CF	Rhtkg (spruce)	4	903	21.1	21.8	15.3	17.9	149
	Mtkg (spruce)	21	1111	19.2	18.9	15.6	18.4	144
	Mtkg (pine)	13	1391	20.5	17.3	14.7	17.4	147
	Ptkg (pine)	78	872	16.1	18.9	15.6	17.7	122
	Vtkg (pine)	34	1015	13.6	15.7	12.2	14.3	84
NOB–K	Rhtkg (spruce)	5	1420	20.0	18.1	12.7	15.4	120
	Mtkg (spruce)	7	1328	19.1	17.9	14.1	17.0	130
	Mtkg (pine)	41	1296	19.0	17.2	14.1	16.4	132
	Ptkg (pine)	44	1131	16.0	16.4	13.3	15.5	106
	Vtkg (pine)	18	1266	12.9	13.9	10.8	12.8	71
Lapland	Rhtkg (spruce)	3*	1637	20.6	16.5	11.4	13.8	113
	Mtkg (spruce)	3*	1824	19.3	16.2	12.7	15.6	118
	Mtkg (pine)	15	1904	20.2	14.6	11.6	14.0	119
	Ptkg (pine)	5	2224	16.4	12.3	9.5	12.3	81
	Vtkg (pine)	3*	2083	12.4	10.6	8.2	10.2	55

2.2 Weather data

We acquired the time series data (2004–2023) from the representative weather stations of the Finnish Meteorological Institute (FMI 2024) for our study regions. Weather data at fine time resolution were aggregated to daily values of mean, maximum and minimum temperature, precipitation, solar radiation and water vapor pressure (Table 3, Fig. 3). Missing weather observations, e.g. due to technical problems of the data provider, were supplemented by searching for the corresponding information at the nearest weather station, secondly by interpolating missing measurements from three previous and three following days, or thirdly by calculating average observations on the same day from different years. Daily water vapor pressure was derived from daily temperature and relative humidity (%) measurements using the equations of Buck (1981). Daily radiation data were obtained from all available stations (a total of seven stations in mainland Finland) and interpolated for our study regions by latitude using inverse distance weighting. A more detailed description of weather data processing is available in Supplementary file S1, available at https://doi.org/10.14214/sf.25025.

Table 3. Annual and midsummer (July–August) weather statistics in our study regions. SF = Southern Finland, CF = Central Finland, NOB–K = North Ostrobothnia–Kainuu.

		SF	CF	NOB–K	Lapland
Annual mean temperature (°C)	min.	3.2	1.7	1.0	–0.7
	mean	5.1	3.8	2.9	1.5
	max.	6.8	5.4	4.5	2.8
July–August mean temperature (°C)	min.	14.5	13.4	13.1	12.5
	mean	16.3	15.2	15.0	14.5
	max.	18.7	17.6	17.1	16.9
Annual rainfall (mm)	min.	434	441	406	387
	mean	644	663	621	539
	max.	814	857	786	754
July–August rainfall (mm)	min.	69	30	34	26
	mean	148	170	168	130
	max.	288	276	303	239
Annual solar radiation (MJ m^{-2})	min.	3053	2933	2887	2613
	mean	3409	3200	3145	2895
	max.	3659	3583	3475	3107
July–August solar radiation (MJ m^{-2})	min.	925	866	825	781
	mean	1034	998	980	901
	max.	1181	1209	1151	1081

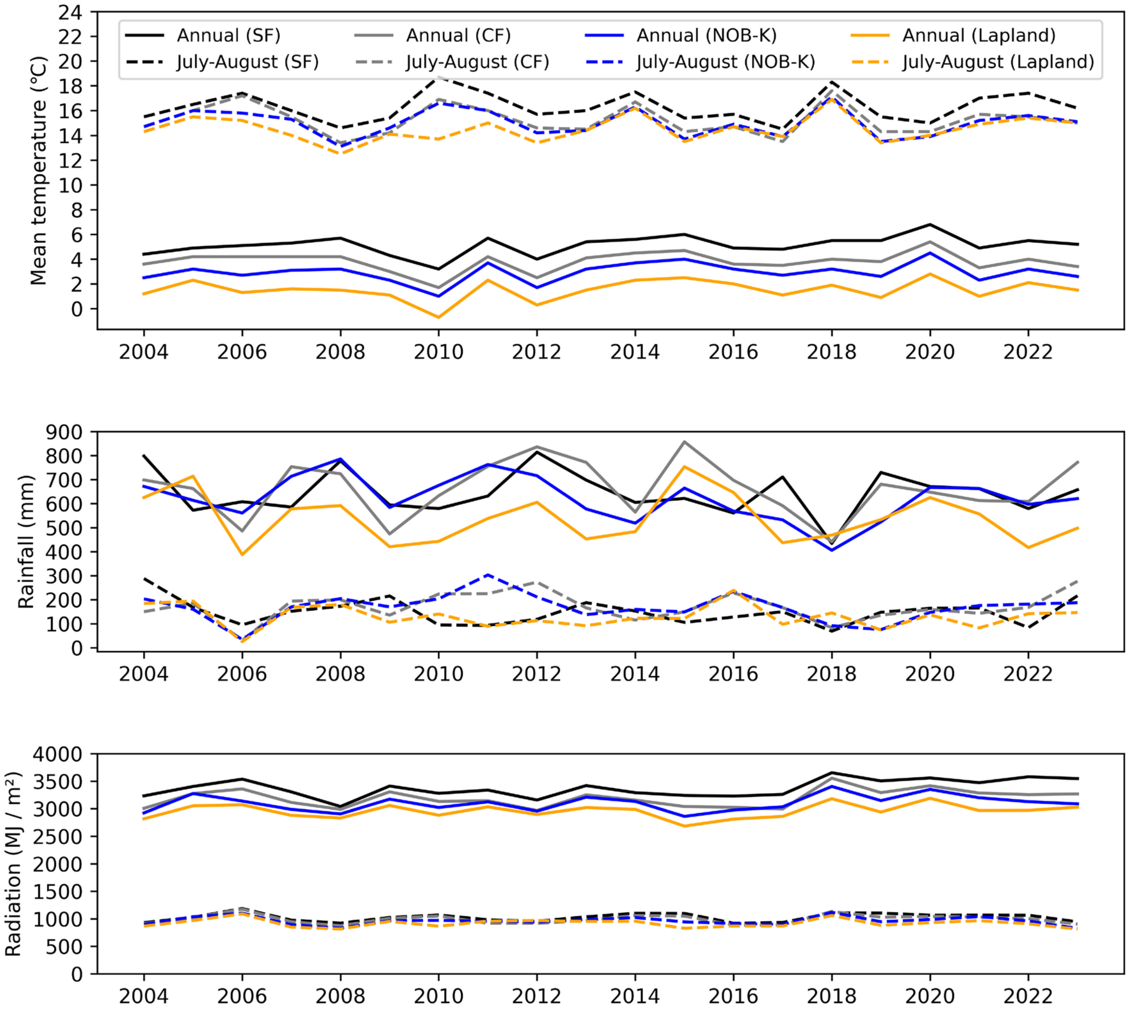


Fig. 3. Annual and midsummer (July–August) temperature, precipitation, and solar radiation during the 20-year simulation period in our study regions. SF = Southern Finland, CF = Central Finland, NOB–K = North Ostrobothnia–Kainuu.

2.3 Simulations

The modeling domain of SUSI consists of a forest stand and a 2-dimensional peat profile between two adjacent ditches (Laurén et al. 2021). Different SFCs had specific peat type and bulk density profiles (Hökkä et al. 2021). We assumed a distance of 40 m between adjacent ditches, which represents a typical ditch spacing in Finnish peatland forests. Peat hydraulic properties were assigned from peat bulk density and peat type as described by Päivänen (1973). *Sphagnum* peat was used for dwarf shrub peatland forests, while combined *Carex* and woody peat properties were used for the other SFCs (Päivänen 1973). The MOTTI stand simulator (Hynynen et al. 2002; Salminen et al. 2005) was used to calculate the allometric roadmap for stand development, including total and assortment volumes and biomass of leaves, branches, stems, roots and stumps (Laurén et al. 2021).

We simulated three ditch depth scenarios (Fig. 2). In the initial ditch depth of 30 cm, it is reasonable to consider DNM, and here the forest manager has three options: doing nothing (NO_DNM), opening the deteriorated ditches to the depth of 90 cm according to current guidelines (DNM_90) or opening the ditches only to the depth of 60 cm (DNM_60). Ditch depths decrease nonlinearly over time so that shallowing rate is highest in deepest ditches (Hökkä et al. 2020). Ditches become shallower due to sedimentation and vegetation ingrowth and simultaneous peat subsidence that lowers the reference level, where the ditch depth is measured. Following Hökkä et al. (2020) at the end of the 20-year simulation period, ditch depths were 20 cm, 40 cm, and 60 cm in the NO_NDM, DNM_60, and DNM_90 scenarios, respectively.

SUSI calculates daily WT, stand net primary production, organic matter decomposition, CO_2 and CH_4 emissions, and nutrient release (Laurén et al. 2021; Palviainen et al. 2024). The annual soil carbon balance C_{soil} [kg ha^{-1} yr^{-1}] was calculated as:

$$C_{soil} = \left(BM_{litter} + BM_{mort} + BM_{LR} + BM_{GV} - BM_{decomp}\right) \times BM_{to}C - DOC_{HMW} - DOC_{LMW}, \quad (1)$$

where BM_{litter} is the mass flux of woody and non-woody litterfall, BM_{mort} is the mass flux of dead trees, BM_{LR} is the mass flux of logging residues, BM_{GV} is the mass flux of ground vegetation litterfall, BM_{decomp} is the mass loss due to decomposition of soil organic matter, $BM_{to}C$ is the ratio of soil carbon to total mass (0.5), and DOC_{HMW} and DOC_{LMW} are the fluxes of high and low molecular weight dissolved organic carbon to downstream water bodies. All fluxes are expressed in kg ha^{-1} yr^{-1}. Furthermore, the annual ecosystem carbon balance $C_{ecosystem}$ [kg ha^{-1} yr^{-1}] was calculated as follows:

$$C_{ecosystem} = C_{soil} + \left(BM_{tree\_growth} + BM_{GV\_change}\right) \times BM_{to}C, \quad (2)$$

where BM_{tree_growth} is the net tree biomass growth [kg ha^{-1} yr^{-1}] and BM_{GV_change} is the biomass change of the ground vegetation [kg ha^{-1} yr^{-1}]. The mass of carbon components (C_{soil} and $C_{ecosystem}$) was then converted to the corresponding mass of CO_2 [kg ha^{-1} yr^{-1}] as follows:

$$mass_{CO_2} = mass_C \times \frac{M_{CO_2}}{M_C}, \quad (3)$$

where the molar mass of CO_2 (M_{CO2}) is 44 g mol^{-1} and the molar mass of C (M_C) is 12 g mol^{-1}. Finally, CO_2 and CH_4 emissions were aggregated into CO_2-equivalent (CO_2eq) emissions using the global warming potential (GWP) of 27 for CH_4 emissions (Forster et al. 2021) as follows:

$$CO_2eq = CO_2 + CH_4 \times GWP_{CH_4}. \quad (4)$$

Annual N and P export loads [kg ha^{-1} yr^{-1}] were calculated by adding the mass of N and P released below the rooting layer to the unused (by trees and ground vegetation) fraction of N and P released in the rooting layer (Laurén et al. 2021). All equations used in the SUSI simulator are openly available in the Zenodo repository (https://doi.org/10.5281/zenodo.17130513). An overview of the simulator's processes is provided in Suppl. file S2, available at https://doi.org/10.14214/sf.25025.

2.4 Economic objectives and trade-offs

We calculated the net present value ($NPV_{DNM\,k}$) [€ ha^{-1}] of the DNM investment in ditch depth scenario k (DNM_60, DNM_90) by comparing the incremental value growth achieved by DNM over 20 years to the cost of operating DNM as follows:

$$NPV_{DNM\,k} = \frac{value_{DNM\,k} - value_{NO\_DNM}}{\left(1 + \frac{i}{100}\right)t} - cost_{DNM}, \quad (5)$$

where $value_{DNM\,k}$ is the value of the forest stand [€ ha^{-1}] in DNM scenario k at the end of the simulation period, $value_{NO\_DNM}$ is the value of the forest stand [€ ha^{-1}] in NO_DNM scenario at the end of the simulation period, i is the discount rate, t is the time in years, and $cost_{DNM}$ is the cost of DNM operation now [€ ha^{-1}]. Sawlog prices of 65.3 € m^{-3} and 67.1 € m^{-3} and pulpwood prices of 24.0 € m^{-3} and 24.9 € m^{-3} were used for Scots pine and Norway spruce, respectively, which represent the inflation-adjusted average stumpage prices for forest thinning in Finland for the years 2021–2024 (OSF 2025a, 2025b). The inflation-adjusted average unit cost of DNM was 1044.8 € km^{-1} (OSF 2024, 2025a). The minimum drainage density is 250 m ha^{-1} when the parallel ditches are spaced 40 meters apart. However, edge and transverse ditches, as well as irregularly shaped drained areas, significantly increase drainage density. For this study, we assumed an average ditch requirement of 300 m ha^{-1}, resulting in a DNM cost of 313.4 € ha^{-1}. Site and scenario specific NPVs were calculated using discount rates of 2%, 3% and 4%.

The cost-effectiveness of DNM in terms of negative climate impacts depends on the trade-offs ($TO_{NPV\,GHG\,k}$) between NPV and varying soil CO$_2$eq emissions [€ kg^{-1}] for the DNM scenario k, which were calculated as follows:

$$TO_{NPV\,GHG\,k} = \frac{NPV_{DNM\,k}}{\left|GHG_{DNM\,k} - GHG_{NO\_DNM}\right|}, \tag{6}$$

where $GHG_{DNM\,k}$ is the 20-year cumulative soil CO$_2$eq emissions [kg ha^{-1}] in the DNM scenario k, and GHG_{NO_DNM} is the 20-year cumulative soil CO$_2$eq emissions [kg ha^{-1}] in the NO_DNM scenario.

Table 4. Average water table below the soil surface during the growing season (May–October) in different regions, site fertility classes (SFC) and scenarios: NO_DNM = no ditch network maintenance, DNM60 = reduced ditch depth of 60 cm, DNM90 = conventional ditch depth of 90 cm. SF = Southern Finland, CF = Central Finland, NOB–K = North Ostrobothnia–Kainuu. SFCs were classified according to Vasander and Laine (2008).

Region	SFC	NO_DNM [m]	DNM_60 [m]	DNM_90 [m]
SF	Rhtkg	–0.47	–0.55	–0.73
SF	Mtkg (spruce)	–0.49	–0.66	–0.95
SF	Mtkg (pine)	–0.43	–0.75	–1.09
SF	Ptkg	–0.35	–0.57	–0.89
SF	Vtkg	–0.26	–0.41	–0.67
CF	Rhtkg	–0.38	–0.51	–0.72
CF	Mtkg (spruce)	–0.34	–0.41	–0.53
CF	Mtkg (pine)	–0.32	–0.51	–0.80
CF	Ptkg	–0.27	–0.37	–0.54
CF	Vtkg	–0.19	–0.27	–0.41
NOB–K	Rhtkg	–0.30	–0.35	–0.45
NOB–K	Mtkg (spruce)	–0.28	–0.31	–0.39
NOB–K	Mtkg (pine)	–0.25	–0.39	–0.62
NOB–K	Ptkg	–0.22	–0.29	–0.41
NOB–K	Vtkg	–0.14	–0.20	–0.30
Lapland	Rhtkg	–0.26	–0.34	–0.49
Lapland	Mtkg (spruce)	–0.25	–0.30	–0.40
Lapland	Mtkg (pine)	–0.23	–0.34	–0.52
Lapland	Ptkg	–0.20	–0.27	–0.36
Lapland	Vtkg	–0.14	–0.21	–0.31

3 Results

Deeper ditches lowered WT, but the magnitude of the lowering was highly dependent on stand location and SFC (Table 4). In our study sites, average growing season WT was 29 cm, 40 cm, and 58 cm in the NO_DNM, DNM_60, and DNM_90 scenarios, respectively. The annual variation in growing season WT is shown in Fig. 4 for four example sites, ranging from the most fertile study site of herb-rich heath forest (Rhtkg) in SF to low-fertility dwarf-shrub peatland (Vtkg) in the NOB–K region. In Rhtkg (SF), late summer WT (July–August) was below 35 cm in 75% of the years also in the NO_DNM scenario. However, in Vtkg located in NOB–K region the late summer WT was below 35 cm only in the dry summer 2006 in the NO_DNM and DNM_60 scenario. In the Norway spruce-dominated Mtkg and Scots pine-dominated Vtkg located in CF region, the ditch depth scenario had a large influence on the number of years in which the growing season WT was optimal (50%–80% in Mtkg, and 35%–85% in Vtkg) for tree growth.

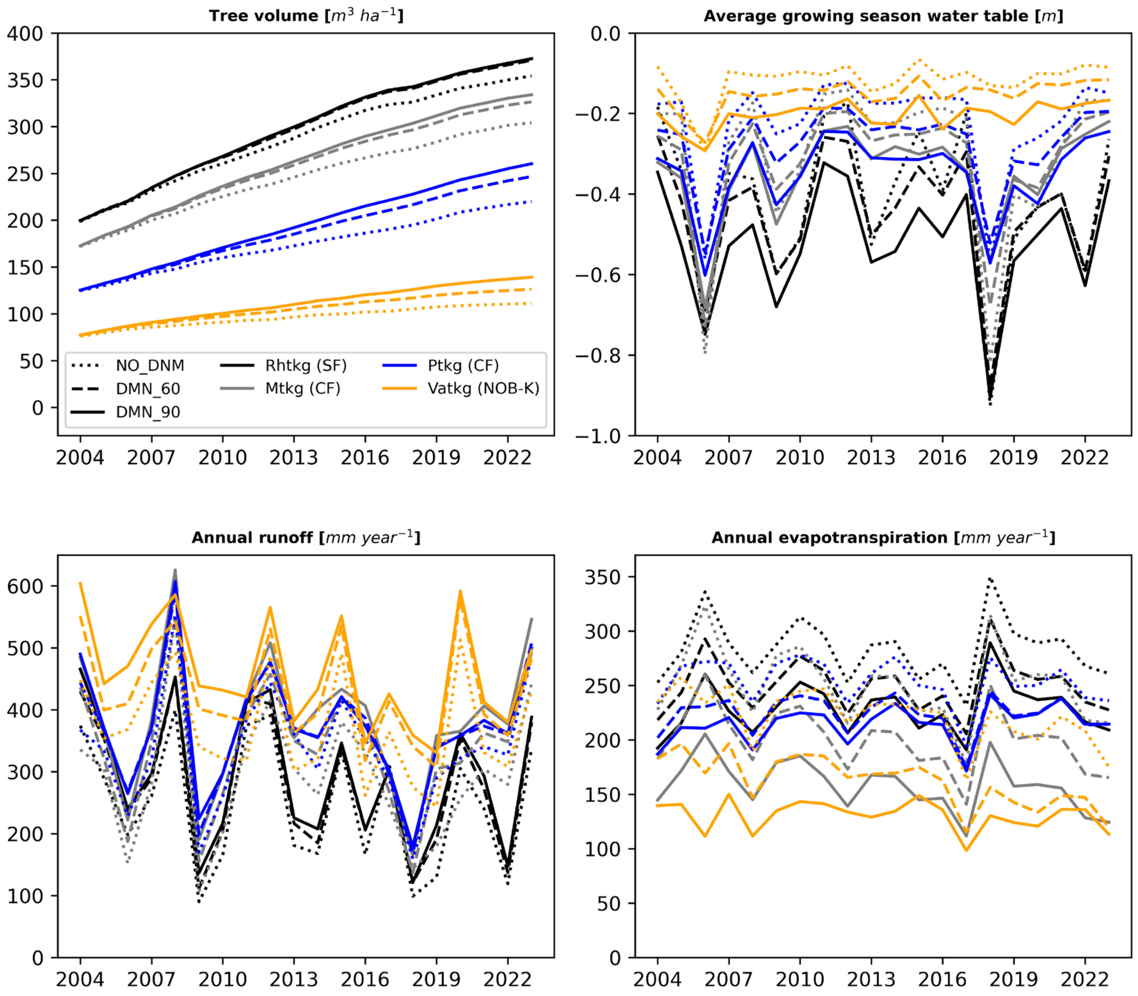


Fig. 4. Tree volume development, variation of the average growing season (May–October) water table below the soil surface, and annual water runoff and evapotranspiration during the 20-year simulation period in four example sites: a spruce-dominated herb-rich heath forest (Rhtkg) in southern Finland (SF), a spruce-dominated *Vaccinium myrtillus*-type peatland forest (Mtkg) and a pine-dominated *V. vitis-idaea*-type peatland forest (Ptkg) in central Finland (CF), and a nutrient-poor dwarf-shrub peatland forest (Vatkg) in the North Ostrobothnia–Kainuu region (NOB–K). Scenarios: NO_DNM = no ditch network maintenance, DNM_60 = reduced ditch depth of 60 cm, NDM_90 = conventional ditch depth of 90 cm.

Tree growth increased by an average of 0.8 $m^3\ ha^{-1}\ yr^{-1}$ and 1.0 $m^3\ ha^{-1}\ yr^{-1}$ in the DNM_60 and DNM_90 scenarios, respectively, compared with the NO_DNM scenario. However, our simulations also showed a negative growth response when WT was too low from the soil surface for optimal tree growth in southern Finland (Table 5). For example, in the Norway spruce-dominated Rhtkg (SF), the average annual growth response was 0.2 $m^3\ ha^{-1}\ yr^{-1}$ in the DNM_60 scenario, but stand growth was predicted to decrease by an average of 0.6 $m^3\ ha^{-1}\ yr^{-1}$ in the DNM_90 scenario. Overall, in more northerly regions, deeper ditches consistently increased stand growth and forest owners may benefit from DNM investments through increased timber production compared to the NO_DNM scenario. The DNM has the highest economic potential in the NOB–K and CF regions (Table 5). In contrast, DNM in the fertile site types (Rhtkg, Mtkg) had negative NPV in SF region. Furthermore, DNM conducted in the nutrient poor Vatkg site yielded in negative NPV in Lapland (Table 5).

Table 5. Average forest volume growth in different regions, site fertility classes (SFC) and scenarios: NO_DNM = no ditch network maintenance, DNM60 = reduced ditch depth of 60 cm, DNM90 = conventional ditch depth of 90 cm. The net present value of ditch network maintenance (NPV_{DNM}) in scenarios DNM_60 and DNM_90 was calculated using discount rates of 2%, 3% and 4%. NPV_{DNM} was not calculated for scenarios with a negative volume growth response to DNM. SF = Southern Finland, CF = Central Finland, NOB–K = North Ostrobothnia–Kainuu. SFCs were classified according to Vasander and Laine (2008).

Region	SFC	Volume growth [$m^3\ ha^{-1}\ yr^{-1}$]			NPV_{DNM} [€ ha^{-1}] (2%)		NPV_{DNM} [€ ha^{-1}] (3%)		NPV_{DNM} [€ ha^{-1}] (4%)	
		NO_DNM	DNM_60	DNM_90	DNM_60	DNM_90	DNM_60	DNM_90	DNM_60	DNM_90
SF	Rhtkg	8.7	8.9	8.1	–94 €		–133 €		–164 €	
SF	Mtkg (spruce)	10.3	10.0	8.7						
SF	Mtkg (pine)	6.9	6.5	6.0						
SF	Ptkg	7.7	8.2	7.5	205 €		113 €		38 €	
SF	Vtkg	5.3	6.1	6.2	338 €	366 €	223 €	246 €	129 €	148 €
CF	Rhtkg	7.6	8.2	7.6	169 €		83 €		14 €	
CF	Mtkg (spruce)	7.9	8.8	8.8	489 €	544 €	347 €	392 €	231 €	268 €
CF	Mtkg (pine)	6.1	6.6	6.3	258 €	–31 €	157 €	–81 €	74 €	–122 €
CF	Ptkg	5.9	7.0	7.3	648 €	882 €	477 €	670 €	338 €	497 €
CF	Vtkg	3.6	4.8	5.6	572 €	1124 €	415 €	869 €	287 €	661 €
NOB–K	Rhtkg	5.5	6.3	6.3	433 €	529 €	301 €	380 €	193 €	258 €
NOB–K	Mtkg (spruce)	6.0	6.9	7.1	460 €	658 €	323 €	486 €	211 €	345 €
NOB–K	Mtkg (pine)	5.7	6.6	6.7	500 €	558 €	356 €	404 €	238 €	278 €
NOB–K	Ptkg	4.8	5.8	6.2	491 €	811 €	349 €	612 €	232 €	449 €
NOB–K	Vtkg	2.5	3.4	4.1	297 €	775 €	189 €	582 €	101 €	425 €
Lapland	Rhtkg	4.1	4.8	4.8	298 €	293 €	190 €	185 €	101 €	98 €
Lapland	Mtkg (spruce)	3.9	4.7	4.9	263 €	417 €	161 €	288 €	78 €	182 €
Lapland	Mtkg (pine)	3.6	4.3	4.6	184 €	351 €	96 €	233 €	24 €	137 €
Lapland	Ptkg	2.9	3.6	3.9	86 €	234 €	15 €	137 €	–42 €	58 €
Lapland	Vtkg	1.5	2.2	2.7	–5 €	191 €	–60 €	102 €	–104 €	29 €

Without DNM, integrated over the whole simulation period, all study sites were carbon sinks at the ecosystem level (Table 6). However, in dry years (e.g. 2006 and 2018), some of the study sites in southern and central Finland were carbon sources even in the NO_DNM scenario due to low WT and consequent high soil CO_2 emissions (Fig. 4, Fig. 5). Soil CO_2 emissions increased almost linearly with WT in the growing season, indicating that omitting DNM or reducing ditch depth are straightforward strategies to improve the climate objectives of peatland forestry. In turn, soils emitted more CH_4 when WT was closer than approximately 30 cm to the soil surface and consume CH_4 at deeper WTs. Compared to the NO_DNM scenario, soil CO_2eq emissions increased on average by 1700 kg ha^{-1} yr^{-1} and 4000 kg ha^{-1} yr^{-1} in the DNM_60 and DNM_90 scenarios, respectively.

Table 6. Average annual soil and ecosystem (soil + biomass) CO_2-equivalent greenhouse gas (GHG) balances in different regions, site fertility classes (SFC) and scenarios: NO_DNM = no ditch network maintenance, DNM60 = reduced ditch depth of 60 cm, DNM90 = conventional ditch depth of 90 cm. A negative value indicates a loss of carbon in soil or biomass (carbon source), and a positive value indicates an addition of carbon storage in forest ecosystem (carbon sink). Trade-offs between net present value (NPV) and increased soil GHG emissions (TO$_{\text{NPV GHG}}$) were calculated using a discount rate of 3%. SF = Southern Finland, CF = Central Finland, NOB–K = North Ostrobothnia–Kainuu. SFCs were classified according to Vasander and Laine (2008).

Region	SFC	Soil GHG balance [kg ha^{-1} yr^{-1}]			TO$_{\text{NPV GHG}}$ (3%)		Ecosystem GHG balance [kg ha^{-1} yr^{-1}]		
		NO_DNM	DNM_60	DNM_90	DNM_60	DNM_90	NO_DNM	DNM_60	DNM_90
SF	Rhtkg	–6860	–8220	–10570			2120	1030	–2150
SF	Mtkg (spruce)	–6530	–8850	–12070			3980	1410	–3100
SF	Mtkg (pine)	–5720	–9610	–13230			1340	–2950	–7130
SF	Ptkg	–4260	–6880	–10840	2 €		3750	1650	–2980
SF	Vtkg	–2910	–5200	–8470	5 €	2 €	2670	1800	–1380
CF	Rhtkg	–5600	–7350	–10070	2 €		2420	1370	–1990
CF	Mtkg (spruce)	–4450	–5440	–7280	17 €	7 €	3650	3580	1840
CF	Mtkg (pine)	–3980	–6110	–9640	4 €		2270	720	–3090
CF	Ptkg	–3160	–4690	–7040	16 €	9 €	3050	2680	680
CF	Vtkg	–1830	–3240	–5220	15 €	13 €	1830	1720	520
NOB–K	Rhtkg	–3830	–4770	–6450	16 €	7 €	2380	2310	760
NOB–K	Mtkg (spruce)	–3020	–3750	–5080	22 €	12 €	3560	3790	2750
NOB–K	Mtkg (pine)	–3360	–5270	–8230	9 €	4 €	2550	1640	–1210
NOB–K	Ptkg	–2110	–3410	–5160	13 €	10 €	2990	2750	1520
NOB–K	Vtkg	–1010	–2280	–3820	7 €	10 €	1550	1240	520
Lapland	Rhtkg	–2800	–4110	–6200	7 €	3 €	2110	1640	–400
Lapland	Mtkg (spruce)	–1840	–2850	–4320	8 €	6 €	2640	2520	1330
Lapland	Mtkg (pine)	–2300	–4070	–6400	3 €	3 €	1620	600	–1420
Lapland	Ptkg	–1220	–2530	–3960	1 €	2 €	1970	1510	420
Lapland	Vtkg	–670	–2090	–3650		2 €	1080	410	–580

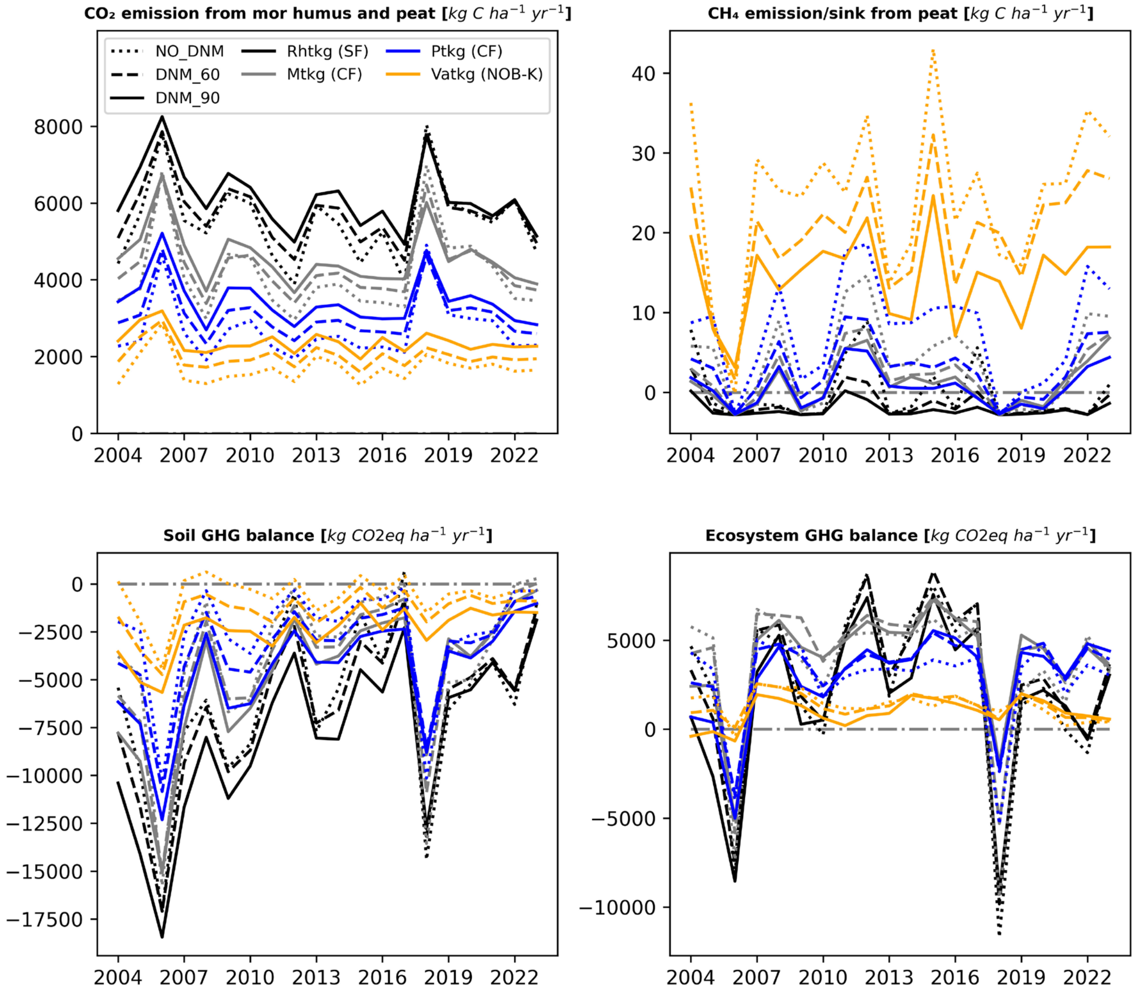


Fig. 5. Annual CO_2 and CH_4 emissions, and CO_2-equivalent soil and ecosystem (soil + biomass) greenhouse gas (GHG) balance during the 20-year simulation period in four example sites (see Fig. 4).

At a discount rate of 3%, the trade-off between the stand NPV and the increased soil GHG emissions was on average 9 € per ton of additional soil GHG emissions in DNM_60 scenario and 6 € per ton in DNM_90 scenario. At the ecosystem level, increased forest volume growth may compensate some of the increased peat decomposition caused by DNM, but in general, the NO_DNM scenario was consistently the best ditch depth alternative in terms of ecosystem GHG balance (Table 6). On average, the ecosystem GHG balance (in CO_2eq) was 2500 kg ha^{-1} yr^{-1}, 1600 kg ha^{-1} yr^{-1}, and –800 kg ha^{-1} yr^{-1} in the NO_DNM, DNM_60, and DNM_90 scenarios, respectively (positive values indicate carbon sinks and negative values indicate carbon sources).

In addition, DNM has a negative impact on downstream water quality, as both N and P export to water courses increased significantly with increasing ditch depth (Table 7), and that the largest nutrient loads occur after dry summers. The annual N exports were 1.6 kg ha^{-1}, 2.3 kg ha^{-1}, and 3.9 kg ha^{-1}, and the annual P exports were 0.3 kg ha^{-1}, 0.4 kg ha^{-1}, and 0.6 kg ha^{-1}, on average, in the NO_DNM, DNM_60, and DNM_90 scenarios, respectively.

Table 7. Average annual nitrogen (N) and phosphorus (P) export in different regions, site fertility classes (SFC) and scenarios: NO_DNM = no ditch network maintenance, DNM60 = reduced ditch depth of 60 cm, DNM90 = conventional ditch depth of 90 cm. SF = Southern Finland, CF = Central Finland, NOB–K = North Ostrobothnia–Kainuu. SFCs were classified according to Vasander and Laine (2008).

Region	SFC	N export [kg ha^{-1} yr^{-1}]			P export [kg ha^{-1} yr^{-1}]		
		NO_DNM	DNM_60	DNM_90	NO_DNM	DNM_60	DNM_90
SF	Rhtkg	4.95	6.53	8.94	1.05	1.20	1.48
SF	Mtkg (spruce)	3.48	4.45	7.05	0.67	0.70	1.00
SF	Mtkg (pine)	2.09	5.36	10.39	0.40	0.90	1.50
SF	Ptkg	1.79	2.32	4.37	0.22	0.26	0.45
SF	Vtkg	1.25	1.96	3.07	0.13	0.19	0.30
CF	Rhtkg	3.59	4.87	7.46	0.87	0.97	1.24
CF	Mtkg (spruce)	2.04	2.39	3.67	0.52	0.58	0.71
CF	Mtkg (pine)	1.92	2.42	4.44	0.38	0.41	0.73
CF	Ptkg	1.17	1.63	2.47	0.17	0.21	0.27
CF	Vtkg	0.65	0.92	1.62	0.06	0.09	0.15
NOB–K	Rhtkg	1.77	2.50	4.27	0.64	0.75	0.93
NOB–K	Mtkg (spruce)	1.10	1.32	2.34	0.35	0.43	0.55
NOB–K	Mtkg (pine)	1.37	1.75	3.28	0.29	0.31	0.50
NOB–K	Ptkg	0.62	1.11	1.89	0.10	0.15	0.22
NOB–K	Vtkg	0.15	0.49	1.05	0.01	0.04	0.09
Lapland	Rhtkg	1.38	2.20	3.93	0.50	0.62	0.77
Lapland	Mtkg (spruce)	0.78	1.16	2.07	0.25	0.35	0.47
Lapland	Mtkg (pine)	1.07	1.54	2.24	0.32	0.30	0.35
Lapland	Ptkg	0.30	0.80	1.44	0.05	0.12	0.19
Lapland	Vtkg	0.08	0.48	1.06	0.01	0.04	0.10

4 Discussion

The rationale of this study was to investigate the effects of ditch depth on timber production, GHG emissions and nutrient export in drained peatland forests located in different geographical regions in Finland. The trade-offs between economic and environmental objectives were evaluated. Field experiments have shown that stand growth is highest when the average July–August WT is 25–30 cm, and no clear growth improvement occurs when WT is lowered below 35–40 cm from the soil surface (Sarkkola et al. 2012). Hökkä et al. (2021) have suggested a depth of 35 cm as an optimal target for peatland WT in late summer. In addition to ditch depth, stand volume is another key factor that affects WT through evapotranspiration. Sarkkola et al. (2010) have suggested that stand volumes of 120 m^3 ha^{-1} and 150 m^3 ha^{-1} are sufficient for keeping WT in optimal range for stand growth in southern and northern Finland, respectively. Our results showed that the lowest growth response to DNM was achieved in southern Finland, where DNM may even have a negative impact on tree growth especially in dry summers. However, our scenarios were based on regional averages of forest attributes, which means that the simulations representing Vtkg–Rhtkg sites in SF and CF were performed on peatland forests, where stand volume is so high that DNM is not recommended (Sarkkola et al. 2010). The highest economic outcome of DNM investment was possible on medium and low fertility drained peatlands in central Finland and NOB–K region.

Among previous empirical studies, Sarkkola et al. (2012) reported average volume growth increases of 0.6 m^3 ha^{-1} yr^{-1} and 1.1 m^3 ha^{-1} yr^{-1} during 20 years after DNM in southern and northern Finland, respectively, when they measured mainly *V. vitis-idaea*- and dwarf shrub-type peatlands at plot locations roughly corresponding to our study regions of CF and NOB–K. In the corresponding regions and SFCs, we simulated average growth responses of 1.0 m^3 ha^{-1} yr^{-1} and

1.7 m^3 ha^{-1} yr^{-1} in the DNM_60 and DNM_90 scenarios, respectively. Sikström et al. (2020) found an average growth response of 1.6 m^3 ha^{-1} yr^{-1} during a 25-year period after DNM in Sweden and the growth response was higher in southern Sweden than in northern Sweden. Ahtikoski et al. (2008) reported mean growth responses of 0.6 m^3 ha^{-1} yr^{-1} – 0.4 m^3 ha^{-1} yr^{-1} for in Lapland (Vtkg) and in North Ostrobothnia (Mtkg), respectively, during 20-year simulation period after DNM.

Lower growing season WT implies increased CO_2 emissions and decreased CH_4 emissions (Ojanen et al. 2010, 2013). Ojanen and Minkkinen (2019) found that when WT was less than 60 cm from the soil surface, net soil CO_2 emissions increased rather linearly with lower WT. Our simulations slightly overestimate the net CO_2 emissions associated with WT compared with the linear models of Ojanen and Minkkinen (2019), but the annual results are still within the range of their empirical data, and the difference between nutrient-rich and nutrient-poor sites is similar. Further validation of the SUSI results would require simulations and gas measurements from the same study sites in the same years. In any case, the hydrological process models of SUSI have been validated against a peatland forest water balance experiment (Sarkkola et al. 2013; Laurén et al. 2021), and the peat decomposition model works logically with respect to soil WT, so it is justified to use these simulations at least to compare GHG emissions between forest management alternatives.

In our results, on average, the DNM_60 and DNM_90 scenarios increased CO_2eq soil emissions by 49% and 119%, respectively, compared to the NO_DNM scenario. At the ecosystem level, which also includes carbon sequestered in aboveground biomass, almost all study sites were carbon sinks when ditch depth was 60 cm, but approximately half of the study sites (including all sites in southern Finland) were carbon sources under the conventional ditch depth strategy. On average, the trade-off between NPV and increased CO_2eq GHG emissions was better in the DNM_60 scenario, where forest owner should be compensated by an average of 9 € per ton of soil GHG emissions if he/she refrains from DNM with reduced ditch depth, compared to the DNM_90 scenario, where the average cost was 6 € per ton of soil GHG emissions. Ahtikoski et al. (2024) reported a cost range of 5–20 € per ton of CO_2 when comparing the respective trade-offs by simulating rotational and continuous cover forestry treatments on drained peatlands in North Ostrobothnia. They used slightly different methods to assess soil CO_2 emissions, different ditch depth assumptions, lower stumpage prices and DNM unit costs, but the price of soil carbon was still in the same range as in our results. In addition, our results are consistent with Eyvindson et al. (2023), who found that maximizing timber production can significantly increase GHG emissions but showed that it is still possible to find reasonable trade-offs between economic benefits and climate goals.

Finland has committed to climate neutrality by 2035 (Huttunen et al. 2022), which means that carbon sinks in the land-use sector will need to be carefully considered in land-use planning and policy-making. Voluntary carbon markets may also develop to allow forest owners to earn income from storing additional carbon in forest biomass (Nonini and Fiala 2021). Note that the price of carbon permits in the European Union has been over 60 € per ton of CO_2 since 2022, which is significantly higher than the price that a rational forest owner should accept for foregoing DNM treatment. In addition, the Water Framework Directive (Carvalho et al. 2019) and the European Union Biodiversity Strategy for 2030 (Hermoso et al. 2022) commit European countries to promote water quality and reverse ecosystem degradation. Furthermore, a growing number of forest owners want to consider environmental and social values in their decision-making (Westin et al. 2023), which requires multi-objective predictions of forest management alternatives for decision support. Our vision is to develop the mechanistic Peatland simulator SUSI into a multi-objective decision support system that can be used when forest owners want to understand how forest management affects the ecosystem and balance conflicting interests in their decision-making. Because SUSI calculates water, nutrient, and carbon fluxes and balances within the ecosystem simultaneously, the economic and environmental objectives can also be modeled simultaneously. Another advantage is that causal interactions can be modeled under climate change and changing site conditions. Understanding these ecosystem interactions holistically is also necessary for calculating peat soil carbon balances, which play a key role in analyzing the carbon balance of Finland's land use sector.

SUSI simulates daily WT, ecosystem carbon and nutrient fluxes, and biomass growth based on soil and forest attributes and daily weather data. In this study, we used weather data from the last 20 years, which caused interannual variability in ecosystem services, especially during the hot and dry summer of 2018. The simulations showed that Norway spruce-dominated fertile peatlands were more vulnerable to drought than Scots pine-dominated nutrient-poor peatlands, suggesting that dry and hot summers can accelerate soil carbon loss, especially in fertile peatlands. Climate scenarios predict an increasing occurrence of droughts in the boreal region (Ruosteenoja and Jylhä 2021), thus the results for 2018 may indicate the direction in which ecosystem services will develop in a warming climate. However, the effects of dry summers on tree growth and other ecosystem services are not straightforward, as there are many feedback mechanisms in peatland ecosystems that need to be understood when considering optimal peatland forest management under the changing climate (Laurén et al. 2021).

Certain assumptions in SUSI require attention in the interpretation of the results. SUSI does not account for soil subsidence, which affects WT gradient and therefore the drain flow. Table 6 reveals that soil is losing C. Converting the C loss to organic material and assuming bulk density of 100 kg m^{-3}, we end up to subsidence estimates of 3–7 cm for NO_DNM scenario and 8–14 cm for DNM_90 scenario during the 20-year simulation period in Southern Finland. For Northern Finland the subsidence rate was smaller. The estimate fits well within the range reported by Minkkinen and Laine (1998), who concluded that peat in Finnish pine mires subsided by 22 cm in 60 years. Shallowing of the ditch in the NO_DNM scenario was altogether 10 cm during the simulation period. We applied the shallowing rate from Hökkä et al. (2020) so that the shallowing rate becomes smaller when the initial ditch depth is shallow. Hökkä et al. (2020) reports ditch depths from field conditions, and the observations implicitly contained both the sedimentation and vegetation ingrowth-driven ditch shallowing and the subsidence-driven drawdown of the reference height (that is the ditch bank or the soil surface). Therefore, even though subsidence was not accounted for in SUSI, the effect of subsidence on the WT gradient became considered implicitly in the ditch shallowing dynamics.

Simulated N and P exports were in some cases higher compared to N (0.2–7.7 kg ha^{-1} yr^{-1}) and P exports (0.01–0.42 kg ha^{-1} yr^{-1}) reported in empirical studies (Finér et al. 2021). SUSI may overestimate the nutrient export loads due to the simplified calculation in which all nutrients released below the rooting zone are transported to water courses in annual time step. This assumption may overestimate the nutrient export especially in dry years and low WTs.

In the future, multi-objective peatland forest management will need to pay more attention to adjusting WT, especially in southern and central Finland climate. Our simulation results and the empirical observations of Hökkä et al. (2025) have shown the risk of decreasing tree growth by overly intensive drainage of peatland forests. The earlier principles that deep WT is required for profitable tree growth should be questioned, as the original drainage is now typically more than 50 years old and soil properties have changed significantly over time, especially due to the development of growing mor layer (Hökkä et al. 2025). In some cases, the optimal solution for balancing forest growth and GHG emissions under the risk of summer drought can be further reducing drainage intensity by blocking part of the ditches or using adjustable dams. Water management planning should be done at the catchment scale, where suitable locations for dams (Urzainki et al. 2020) and/or water protection structures (Niemi et al. 2023) can be optimized using hydrological models and spatial analysis. In any case, process-based ecosystem modeling allows prediction of forest development under global warming and offers great potential for research on multi-objective forest planning.

5 Conclusions

Multi-objective forest owners need information on the multiple ecosystem services of different forest management alternatives, and in this study, we presented how the process-based Peatland simulator SUSI can be used to evaluate the conflicting economic and environmental objectives of different ditch depth alternatives. In our simulations, annual stand growth increased by an average of 14% and 18% in the reduced and conventional ditch depth scenarios, respectively, compared to the 30 cm ditch depth scenario. However, soil GHG emissions increased by 49% and 119%, N leaching by 46% and 144%, and P leaching by 23% and 72% in the 60 cm and 90 cm ditch depth scenarios, respectively. The financial return of DNM depends strongly on stand characteristics, site fertility and soil location. Our results showed a positive NPV for DNM investments at a 4% discount rate in all the study sites located in central Finland and North Ostrobothnia–Kainuu region, but in southern Finland DNM may even have negative effect on tree growth due to over-drainage. Over the 20-year simulation period, our results showed that less intensive drainage is a cost-effective approach to mitigate climate change, as the trade-off between NPV and CO_2 emissions ranged from 0–22 € per ton CO_2, which is a very moderate cost in carbon units compared to market prices or other alternatives to produce these credits. Future developments of our research will focus on different harvesting treatments, fertilization alternatives and the use of climate change scenarios for decision support in multi-objective peatland forestry.

Supplementary files

S1.pdf,
S2.pdf,
Metadata of research data.pdf,
available at https://doi.org/10.14214/sf.25025.

Declaration of openness of research materials, data, and code

The forest and weather data were obtained from open data sources of the Natural Resources Institute of Finland (2023), the Finnish Forest Centre (2023) and the Finnish Meteorological Institute (2024). The source code of the SUSI simulator is openly available at https://github.com/annamarilauren/susi_2024. All data, code and supplementary files are openly available at the Zenodo data repository: https://doi.org/10.5281/zenodo.17130513.

Authors' contributions

All authors contributed to the conception of the research question and design of the work. M.N. processed the forest and weather data, A.L. implemented the simulations, and M.N. analyzed the results. All authors contributed to the critical revision of the results and scientific writing.

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