

Trade-offs between nutrient export, greenhouse gas balance and financial performance in continuous cover and rotation forestry in drained peatlands in northern Finland

Anssi Ahtikoski¹, Jaakko Repola², Hannu Hökkä³, Sakari Sarkkola⁴,
Paavo Ojanen⁴, Soili Haikarainen⁴, Leena Stenberg⁵, Artti Juutinen³

¹Natural Resources Institute Finland, Tampere, ²Natural Resources Institute Finland, Rovaniemi,

³Natural Resources Institute Finland, Oulu, ⁴Natural Resources Institute Finland, Helsinki,

⁵Natural Resources Institute Finland, Joensuu, Finland

SUMMARY

Boreal peatlands comprise one of the largest terrestrial carbon pools, provide a variety of ecosystem services, and are important for biodiversity. The characteristic multifunctionality of peatland forests calls for research that is able to assess trade-offs between marketed (timber) and non-marketed (water quality, greenhouse gas balance) public goods. Once the trade-offs are revealed, it becomes feasible to pursue sustainable forest management. An openly available database was used to derive an empirical dataset representing a miniature of the Kiiminkijoki catchment in northern Finland, which was used for stand-level simulations (Motti stand simulator) and landscape-level optimisation in drained peatland forests. For each initial state, stand projections were simulated for rotation forestry (RF) and continuous cover forestry (CCF) management. The rationale was to investigate trade-offs between nutrient export, greenhouse gas balance and net present value (NPV). The cost efficiency of reducing greenhouse gas emissions and nutrient export was calculated by optimising forest management (both RF and CCF) within the Kiiminkijoki catchment. The results suggested that applying both RF and CCF in drained peatlands constitutes a highly cost-effective way to reduce greenhouse gas emissions, the cost range being € ~5–20 per tonne of CO₂. However, the nitrogen equivalent (NE) cost of reducing nutrient export tends to be quite high (€ 17–58 kg⁻¹) compared to values for mineral soils provided by existing literature.

KEY WORDS: landscape, Motti stand simulator, optimisation, peatlands, stand level

INTRODUCTION

Forest ecosystems account for approximately 80 % of aboveground terrestrial carbon and 70 % of soil organic carbon (Dixon *et al.* 1994, Hui *et al.* 2015). They are also net carbon sinks (Pan *et al.* 2011), and the forest sector is seen as an important contributor towards reaching climate mitigation objectives (Eriksson 2015, Riviere & Cauria 2021). Boreal forests play a key role in carbon uptake because, after wetlands, they are estimated to contain the highest carbon stocks per unit area (IPCC 2001). Boreal peatlands are one of the largest terrestrial carbon pools globally (Bradshaw & Warkentin 2015). In total, about 15 million hectares of peatland have been drained for forestry in the boreal and temperate zones, providing an economically important source of woody biomass (Paavilainen & Päivänen, 1995). In Finland, approximately 4.7 million hectares of drained peatland constitute an integral part (23 %) of the total productive forestland area (Korhonen *et al.* 2017).

Drainage can turn unproductive peatlands to timber production (MacDonald & Yin 1999,

Päivänen 2007), although Nordic countries are no longer draining pristine peatlands (Päivänen & Hånell 2012). In previously converted peatlands, ditch bank erosion and vegetation colonisation gradually reduce water movement in the ditches and raise the ditch water level. This causes re-wetting and may reduce tree growth. To prevent this, ditch network maintenance (DNM) is commonly carried out (Sikström & Hökkä 2015). In rotation forestry (RF), DNM is usually conducted 1–2 times within a rotation (of 80–100 years) and specifically in connection with clearcutting (Sikström & Hökkä 2015, Hökkä *et al.* 2017). Drainage improves tree growth (e.g., Ahti *et al.* 2008, Sikström *et al.* 2020), but at the same time causes negative side effects: a pulse of suspended solids (SS), nutrients (mainly phosphorus and nitrogen) and dissolved organic carbon is exported to surface waters (Finér *et al.* 2021). Of particular concern are headwater catchments, where forestry may be the predominant local contributor of nutrient exports to watercourses (Finér *et al.* 2010) which are highly sensitive to effects of eutrophication, increased siltation and



turbidity (Turunen 2018). Various water protection measures such as overland flow fields, sedimentation ponds and peak runoff control dams (e.g., Miettinen *et al.* 2020) are applied to prevent nutrient and sediment export, but these are costly and, more importantly, their efficiency varies considerably (Haahti *et al.* 2018, Nieminen *et al.* 2018a). Another environmental drawback associated with forestry practice on drained peatlands is carbon dioxide (CO₂) emissions due to the increased heterotrophic soil respiration and accelerated decomposition of the aerated peat layer. In high-volume mature stands, especially in the most nutrient-rich sites with deep peat layers, clear-cutting (in particular) can result in such large carbon emissions that forestry drained peatlands become net CO₂ sources (Korkiakoski *et al.* 2023). Nitrous oxide (N₂O) emissions from the dry peat profile also present environmental drawbacks (e.g., Ojanen *et al.* 2013, Korkiakoski *et al.* 2023). These emissions are caused by the biological consequences of drainage sustained by the high rate of evapotranspiration in high-volume stands (Sarkkola *et al.* 2010, Hökkä *et al.* 2021).

To avoid detrimental effects associated with RF (nutrient and sediment export, as well as greenhouse gas emissions from soil), alternative management practices can be chosen. One such alternative is continuous cover forestry (CCF), which applies partial felling methods (Bose *et al.* 2014). CCF avoids clearfelling and relies on natural regeneration. In most cases, it also refrains from site preparation (Pommerening & Murphy 2004). In CCF only a subset of the trees is harvested, and a considerable number of trees is retained to maintain forest cover (Appelqvist *et al.* 2021). Because the tree stand is the second most crucial factor in regulating the peatland water table (Sarkkola *et al.* 2010), maintaining a continuous tree cover with adequate evapotranspiration capacity could reduce or even exclude the need for regular DNM operations (Sarkkola *et al.* 2010, 2013), resulting in a more stable water table in CCF than in RF. This, in turn, would be favourable for water quality (Nieminen *et al.* 2018b, Leppä *et al.* 2020). Moreover, CCF makes it possible to manage water table level and concurrently reduce soil disturbance (compared to RF), so the cascading effects of water table control may not only reduce greenhouse gas emissions, but also simultaneously improve biodiversity (Laudon & Hasselquist 2023).

Recent literature has shown CCF to be preferable to RF from both economic (e.g., Juutinen *et al.* 2018a, Parkatti *et al.* 2019, Parkatti & Tahvonen 2020) and environmental perspectives (Nieminen *et al.* 2018b, Peura *et al.* 2018). However, CCF involves

substantial uncertainties such as ingrowth by natural regeneration (Saksa & Nerg 2008, Lappi & Pukkala 2020), growth of large trees more than 1.3 m in height (Hynynen *et al.* 2019, Bianchi *et al.* 2020) and damage risks (remaining trees and roots) associated with harvests (Nevalainen & Piri 2020). Growth of large trees and damage risks tend to be particularly divergent from the situation under RF. With regard to carbon sequestration, it seems that a higher carbon emission trading price extends the felling cycle and increases the average tree capital in CCF (Assmuth *et al.* 2018, 2021; Parkatti & Tahvonen 2021). This also seems to apply to RF (Niinimäki *et al.* 2013, Pihlainen *et al.* 2014). To date there have been only a few studies either tackling financial comparison between CCF and RF (Juutinen *et al.* 2021) or prioritising between minimum net greenhouse gas balance, economic timber value and income-flow requirements from timber in boreal peatland forests (Eyvindson *et al.* 2023). Furthermore, the current literature lacks studies focusing on the cost-efficiency of carbon sequestration in boreal peatland forests when there is a free choice between CCF, RF, and their combination at landscape level. Such information is urgently needed for decision-making in the land-use sector.

The purpose of this study was to first investigate trade-offs between nutrient export, greenhouse gas balance and net present value (NPV) in drained boreal peatland forests when either RF or CCF is applied, then to assess the cost-efficiency of reducing greenhouse gas emissions and nutrient export by optimising forest management between CCF and RF, in drained boreal peatland stands located within a target region in northern Finland. The time period for assessing the greenhouse gas balance and nutrient export was set to 50 years, corresponding roughly to the period ending in the year 2070 which is a possible net-zero target for energy systems (IEA 2020). The optimisation was conducted using alternative interest rates to discover how sensitive the cost-efficiency is to different returns on capital. Technically, the cost-efficiency calculation was solved through mixed-integer optimisation which resolves maximum NPV, minimum greenhouse gas emissions, and minimum nutrient export. Furthermore, we examined how much the inclusion of soil greenhouse gas balance affects cost-efficiency compared to a situation where only carbon sequestered in tree biomass is included. The latter analysis provides new insights on the feedback mechanism between felling strategy and soil greenhouse gas balance in monetary terms. Finally, a sensitivity analysis involving an alternative time period (20 years) was conducted to explore the effect of timescale on the results.

METHODS

Data

Forest data from the Kiiminkijoki catchment area (Figure 1) were extracted from an openly available database managed by the Finnish Forest Centre (FFC 2022), and filtered to include only drained peatland stands dominated by Scots pine (*Pinus sylvestris* L.) because such stands represent over 70 % of all peatland forest stands in northern Finland (Korhonen *et al.* 2017). The data included stand-level information by tree species along with information on site type classes (Table 1). In general, the data encompassed young and advanced (pre-mature) thinning stands (Table 1) with average age >30 years, prior to clearfelling phase.

The simulation data were constructed as follows. First, we categorised the catchment area according to dominant tree species (Scots pine or Norway spruce (*Picea abies*, Karst. L.)) and site type (Herb-rich type, *Vaccinium myrtillus* type II, *Vaccinium vitis-idaea* type II or dwarf-shrub type, according to the site type classification of drained peatlands (Laine *et al.* 2012)), which we then ranked in terms of area so that we finally included a total of six site types. These site types covered >98 % of the drained peatland forest within the catchment area. Secondly, for each species - site type combination we calculated arithmetic averages of tree stand age, height, mean diameter, basal area and stem number (shown in

Table 1). Thirdly, for the most representative species - site type combinations (each covering > 8 % of the total catchment area), we also applied quartiles to mimic variation (see Table 1 for details). As a result we obtained eleven simulation stands altogether, to comprehensively represent the dominant tree species, site types and stand properties on drained peatlands in the Kiiminkijoki area (Table 1). These simulation stands were fed as inputs into the Motti stand simulator.

For the simulations we constructed a miniature catchment (hereafter ‘miniature’) to represent the original catchment area. The miniature consisted of drained peatland sites and stand structures in identical proportions to those in the real catchment area. The rationale of establishing the miniature was to apply stand-level simulations in combination with hydrological modelling, and thus to enable a detailed assessment of soil greenhouse gas balance. Applying this approach to the whole catchment area, which contains over 17,000 individual stands of average area 0.7 ha covering approximately 13,000 hectares in total, would have required enormous computational capacity since daily weather data were applied in hydrological modelling of the water table (WT). Instead, we employed a miniature of 1,000 hectares representing an identical forest structure and thus describing the catchment area in a relevant manner, but with a considerably smaller computational requirement.

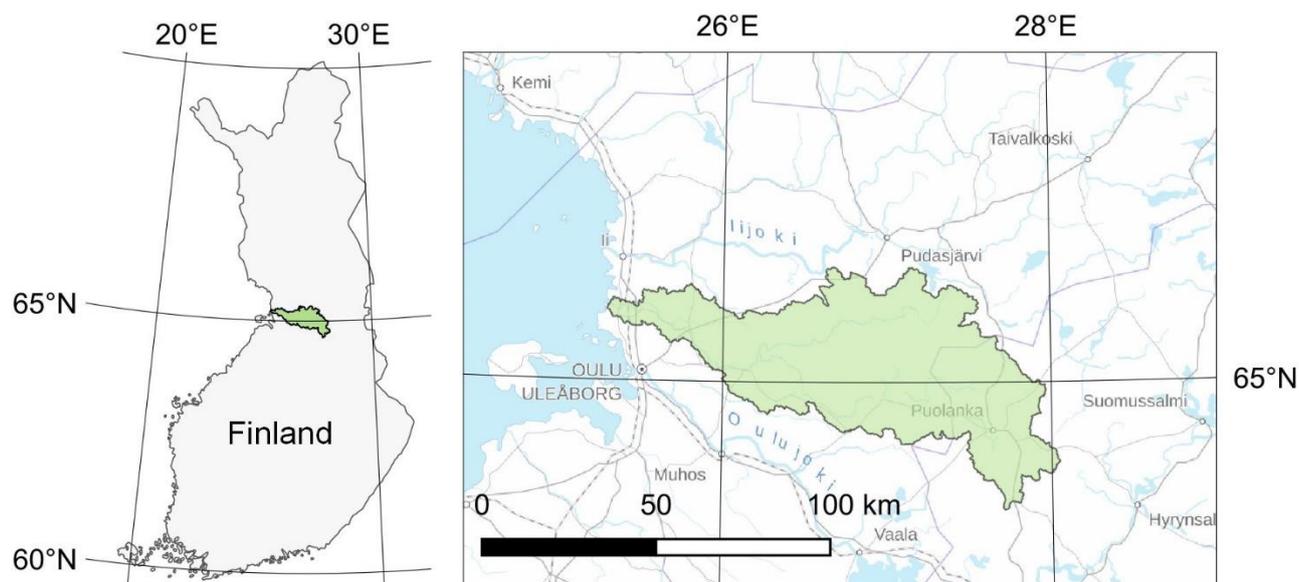


Figure 1. Location of the Kiiminkijoki catchment area. Kiiminkijoki catchment area shape file © Finnish Environment Institute, August 2023. Background map raster © the National Land Survey of Finland, August 2023.

Table 1. Initial stand characteristics for the simulation stands included in this study. The names of site types follow the Finnish site classification system of forestry-drained peatlands (Laine *et al.* 2012). Grey-shaded site types represent pine peatlands while spruce peatlands are presented without shading. The total area consisting of different peatland site types corresponds to the area of the miniature (1,000 hectares). Variables in bold were fed as input into the Motti simulator to represent a stand corresponding the particular simulation stand. Values of the variables (Age, Mean height, Mean diameter, Basal area, Stem number) are arithmetic averages or quartiles corresponding each site type, derived from the original data for the catchment area.

Simulation stands by site type and stand properties (from poorest to most fertile)	Area (ha) ²⁾	Age (years)	Mean height (m)	Mean diameter (cm)	Basal area (m ² ha ⁻¹)	Stem number (ha ⁻¹)	Volume (m ³ ha ⁻¹)
Dwarf-shrub type ¹⁾ average	206	59 ³⁾ 58 46	11.0 10.0 10.1	14.6 13.1 11.0	8.8 1.2 1.2	747 116 150	51.9 6.8 6.4
Dwarf-shrub type upper quartile ⁴⁾	32	65 70 54	15.3 13.6 13.2	19.1 17.5 14.0	15.8 3.7 4.0	723 211 335	119 25.6 25.4
<i>Vaccinium vitis-idaea</i> type II lower quartile	60	47 42 34	9.2 7.6 7.5	11.9 10.3 8.3	5.3 0.4 0.6	813 68 205	27.5 1.9 2.7
<i>Vaccinium vitis-idaea</i> type II average	495	61 61 50	13.5 11.6 11.5	17.3 15.4 13.1	12.4 1.8 1.9	767 132 189	83.7 10.4 10.7
<i>Vaccinium vitis-idaea</i> type II upper quartile	48	67 73 57	16.1 14.5 13.7	20.7 19.4 15.0	15.7 4.5 5.0	611 215 386	123.8 31.8 33.0
<i>Vaccinium myrtillus</i> type II lower quartile	8	50 49 39	10.3 9.2 9.3	13.7 12.8 10.8	6.2 1.4 1.1	641 168 372	36.3 6.9 5.3
<i>Vaccinium myrtillus</i> type II average	66	64 67 53	15.0 13.1 12.8	19.5 17.8 14.4	12.9 3.1 3.1	581 175 258	95.7 19.9 18.6
<i>Vaccinium myrtillus</i> type II upper quartile	8	72 77 63	16.9 15.3 14.5	21.7 21.0 16.0	15.1 6.5 7.3	512 259 497	123.9 47.2 49.2
<i>Vaccinium vitis-idaea</i> type II average	22	57 60 50	13.4 11.9 12.1	17.9 16.3 13.8	8.3 4.8 5.2	494 350 540	57.0 29.8 31.6
<i>Vaccinium myrtillus</i> type II average	47	62 66 55	14.5 13.4 13.1	19.7 18.9 15.3	8.2 6.3 7.0	365 319 556	61.0 42.3 45.3
Herb-rich type average	8	59 66 52	14.4 13.4 13.3	18.8 18.3 15.0	7.2 6.0 7.7	316 280 519	54.6 41.0 51.0

¹⁾For forestry-drained peatland site types, see Laine *et al.* 2012; ²⁾for instance, 206 ha within the 1,000 ha miniature (206/1,000) corresponds to the proportion (20.6 %) of the particular peatland site type in the original catchment area; ³⁾uppermost value is the variable value for pine (59 years), the middle value is for spruce (58 years) and the lowermost value is for birch (46 years); ⁴⁾quartiles (upper: 90 %, lower 10 %) were applied in cases where the proportion of the particular peatland site type in the original catchment area exceeded 8 % (for Dwarf-shrub site type the lower quartile was not calculated owing to obsolete stratum data). The rationale of applying quartiles was to capture the variation within the original forest data for the Kiiminkijoki catchment area; “average” means an arithmetic mean for all sites belonging to the particular peatland site type

Simulations of stand dynamics

For both forestry systems (CCF and RF), stand projections were produced using the Motti stand simulator. The Motti stand simulator is a stand-level decision support tool for assessing the effects of forest management on stand dynamics (Salminen *et al.* 2005, Hynynen *et al.* 2015). The core of Motti is a stand simulation module consisting of stand level and individual-tree level models, both based on an empirical-statistical modelling approach (e.g., Hynynen *et al.* 2015). Natural regeneration and early growth models are based on stand-level modelling, while for established trees (dominant height > 7 m), predictions are based on sample trees each representing a certain number of trees per hectare and simulated with individual-tree models (for technical details of the models, see Supplementary Data in Juutinen *et al.* (2018b)). The Motti stand simulator has been widely applied in research which deals with tree growth and stand management (see, e.g., Mönkkönen *et al.* 2014, Pingoud *et al.* 2018, Ahtikoski & Hökkä 2019). Recently, Motti has been incorporated into new models describing, for example, the effect of shading on ingrowth in Scots pine stands on peatland which are managed by strip felling (Ahtikoski *et al.* 2022), strip felling being the CCF method used in stands dominated by Scots pine. In Norway spruce dominated stands the CCF method applied is selective felling.

The simulations were started from the initial stand data, which were fed into the Motti stand simulator as input (see Table 1). Simulations were conducted to infinity meaning that, in the case of RF, stand management for the ongoing rotation was simulated first and after that the next generation was simulated starting from bare land with planting (technically, the identical next generation was repeated to infinity). In the case of CCF, a conversion phase was simulated first. During the conversion phase (transition period), selective felling and natural regeneration were applied such that the stand transitioned gradually into a steady state in which an equilibrium distribution with a fixed harvesting interval was maintained to infinity. The conversion phase could take several decades, depending crucially on the initial stand structure (e.g., Pommerening & Murphy 2004). Technically, the conversion phase was simulated by following current silvicultural recommendations (Äijälä *et al.* 2019, p. 113) which provide guidelines for the basal area range (expressed in $\text{m}^2 \text{ha}^{-1}$) to be attained in CCF. In the case of RF, the silvicultural guidelines (Äijälä *et al.* 2019) adopted for the simulations were based on thinning limits (basal area expressed as a function of dominant height; exceeding the given limit triggers thinning) and

rotation periods specific to soil type and main tree species (Äijälä *et al.* 2019). CCF was simulated according to a procedure in which the felling cycle and thinning intensity were altered so that the resulting management regime for each peatland site type was feasible in terms of forestry practice (e.g., securing felling removals and growing stock that were both reasonable). Examples of stand development in RF and CCF simulations are presented in Figure 2.

Water table dynamics

Daily WT was simulated for 50 years using the process-based hydrological module of the SUSI model (Laurén *et al.* 2021), following the stand projections described above. SUSI calculates aboveground and belowground hydrology in a transect between two ditches using a daily time step. We used similar weather data for every year in order to enable evaluation of the differences between RF and CCF (in particular) as well as between different peatland site types. Daily weather data for the year 2009, from the weather station in Kiiminki municipality (annual precipitation 540 mm, June–August precipitation 194 mm, June–August mean temperature 14.5 °C), were chosen to represent average conditions in the catchment. The weather data were obtained from the Finnish Meteorological Institute’s 10 × 10 km grid data (Venäläinen *et al.* 2005). Peat parameterisation (water retention characteristics and hydraulic conductivity) followed a previous study (Hökkä *et al.* 2021); i.e., for dwarf-shrub sites *Sphagnum* peat was assumed, and for other peatland site types *Carex* peat was assumed

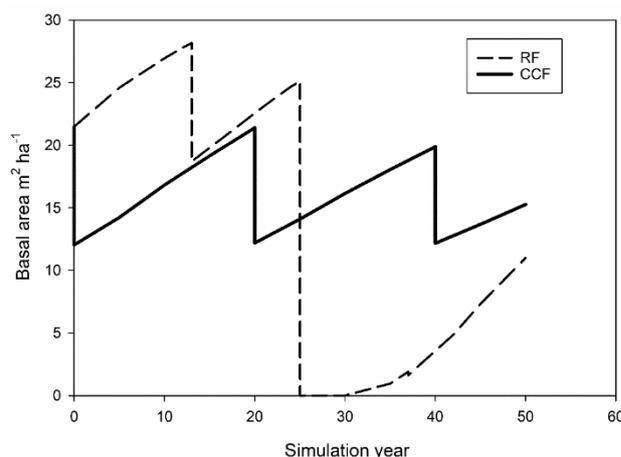


Figure 2. Example of simulated development under RF (dashed line) and CCF (solid line) over a 50-year period for *Vaccinium myrtillus* type II. In RF, clearfelling occurs in year 25 of the simulation.

(see Table 1). Ditch spacing was assumed to be 40 m in all cases. Ditch depth was assumed to be 0.5 m until DNM which deepened the ditch to 0.8 m (as in current recommendations). After DNM the ditch depth was assumed to decrease linearly back to 0.5 m over the next 30 years, which roughly follows the typical shallowing rate of peatland forest ditches (Hökkä *et al.* 2020). In this study the simplified linear shallowing rate was applied in SUSI for technical reasons, to enable the simulation to continue from the correct ditch depth after felling operations. For greenhouse gas balance and nutrient export estimations, we calculated average simulated WT between the two ditches for May–October and August of each year, respectively.

Greenhouse gas balance

In this study, greenhouse gas emissions (sources) are presented as positive values (positive balance). Negative balance represents a sink. The greenhouse gas (GHG) balance included CO₂ balance due to changes in living tree biomass (tree growth and felling) and soil CO₂, N₂O balance and methane (CH₄) balance. Soil CO₂ balance is the difference between heterotrophic soil respiration and litter production (Ojanen & Minkkinen 2019). Carbon (C) storage changes in logging residues and wood products were not taken into account. Greenhouse gas balance was calculated as a sum for the whole simulation period of 50 years. Living tree biomass included stem, living and dead branches, foliage, stumps, coarse roots and fine roots. Dry biomass (expressed in tonnes, *t*) was first converted into C mass (*t*) by applying a coefficient of 0.5 (Penman *et al.* 2003) to determine total C content. Then, C mass was converted into CO₂ mass by applying a coefficient of 3.67 (Penman *et al.* 2003), which is the atomic weight quotient of CO₂ and C (44/12).

To estimate soil GHG balance, we linked the May–October mean WT obtained from the hydrological module of the SUSI model (Lauren *et al.* 2021) to statistical models for estimating the annual GHG balance of forestry-drained boreal peat soils for CO₂ (Ojanen & Minkkinen 2019), N₂O (Minkkinen *et al.* 2020) and CH₄ (Ojanen *et al.* 2010). The deeper the WT, the higher the CO₂ and N₂O emissions and the lower the CH₄ emissions from the soil. The CO₂ and N₂O emissions are also higher on more fertile compared to less fertile site types. CH₄ emissions from ditches (Rissanen *et al.* 2023) were included, assuming 40 m ditch spacing, 1 m ditch width, 67 % moss-covered ditches and 33 % moss-free ditches. To aggregate the GHG balances into a single value, we converted CH₄ and N₂O balances to the 100-year global warming potential

CO₂-eq. values, using 298 for N₂O and 34 for CH₄ (Stocker *et al.* 2014).

Nutrient export

The nutrient export caused by RF and CCF practices was determined for the whole simulation period of 50 years. The so-called nitrogen equivalent (NE) factor sums up the nitrogen and phosphorus loads (Miettinen *et al.* 2020) in terms of their effects in causing eutrophication. In this context, one phosphorus load unit corresponds to 7.2 nitrogen load units, which reflects the ratio of phosphorus to nitrogen in aquatic plankton (Wetzel 2001). Thus, the nitrogen equivalent is calculated as follows:

$$NE = \text{TotN} + 7.2\text{TotP} \quad [1]$$

where NE is nitrogen equivalent (kg ha⁻¹), TotN is the export of total nitrogen (kg ha⁻¹) and TotP is the export of total phosphorus (kg ha⁻¹) during the time period of 50 years.

The primary contributors to nutrient export from drained peatland sites are forest management practices such as harvesting, DNM and fertilisation (Finér *et al.* 2010). Also, substantial long-term nutrient inputs result from initial drainage of the site (additional drainage effect) owing to the lowered WT, accelerated peat decomposition and consequent release of nutrients (Nieminen *et al.* 2021, 2022). The calculations of nitrogen and phosphorus exports were based on: i) estimation of the drainage effect by the SUSI model (Laurén *et al.* 2021), as averaged by Nieminen *et al.* (2023), taking into account site fertility and WT; and ii) new information about nutrient exports caused by forestry treatments in peatlands, where the amounts of nitrogen and phosphorus exported are correlated with the amount of wood (stand volume) removed by harvesting (Nieminen *et al.* 2023). The effects of DNM included in RF simulations were taken into account such that DNM lowered the water level and further increased peat decomposition, which in turn increased the nitrogen and phosphorus loads (additional drainage effect). TotN and TotP loads were calculated annually, and the 50-year NE values were calculated by summing up the annual loads.

Profitability

Net present value (NPV)

NPV was defined as the profitability of both CCF and RF. For CCF the NPV (€ ha⁻¹) was calculated in the following way. Let felling revenues (including sawlogs and pulpwood) be denoted by CR_t^l where l is the l^{th} felling during the conversion phase, $l = 1 \dots$

L at time t_i and the duration of the conversion phase is t_T . The discount factor is $b = 1/(1+r)$ where r is the interest rate. At steady state, CR_{t_s} indicates cutting revenues within a cutting cycle t_s . Given this notation, the NPV (€ ha⁻¹) for CCF was calculated as:

$$NPV_{CCF} = \sum_{i=0}^T b^{t_i} \sum_{l=1}^L CR_{t_i}^l + \frac{b^{t_s * CR_{t_s}}}{1 - b^{t_s}} * b^{t_T} \quad [2]$$

The first term on the right-hand side of Equation 2 describes the NPV of the conversion phase by summing up the felling revenues (CR) occurring at different times t_i during the conversion phase $\{t_0, t_T\}$ and further discounting them by a discount factor b for each time t_i felling takes place. The second term represents the NPV of felling revenues during the steady state with a fixed felling cycle of t_s years, and is further discounted from the end of the conversion phase (t_T) to the present (t_0) by a discount factor b with an exponent t_T . For instance, t_0 could be 0, t_1 18 years, t_T 43 years and t_s 25 years indicating that the first felling in the conversion phase occurs at year 0, the second felling at year 18 and the conversion phase ends at year 43, when a steady state is achieved. Then the felling cycle of the steady state is 25 years.

The NPV (in € ha⁻¹) for RF was assessed as follows. Let $CR_{t_i}^k$ be felling revenues (including sawlogs and pulpwood) from the k^{th} felling in the ongoing rotation at year t_i (t_T denotes the timing of clearfelling in the ongoing rotation, in years). Felling revenues from the h^{th} felling in the next generation are denoted by $CR_{t_n}^h$ at year t_n , $h = 1 \dots H$ so that $CR_{t_N}^H$ indicates felling revenues from a clearfell at rotation end. Then, $sc_{p_{t_m}}$ is the silvicultural cost of measure p (e.g., soil preparation) at time t_m , $p = 1 \dots P$. The discount factor (b) is identical to that in Equation 2. Note that $t_M < t_N$. The NPV (€ ha⁻¹) for RF was calculated with:

$$NPV_{RF} = \sum_{i=0}^T b^{t_i} \sum_{k=1}^K CR_{t_i}^k + \frac{\sum_{n=1}^N b^{t_n} \sum_{h=1}^H CR_{t_n}^h - \sum_{m=0}^M b^{t_m} \sum_{p=1}^P sc_{p_{t_m}}}{1 - b^{t_N}} * b^{t_T} \quad [3]$$

In Equation 2 the first term on the right-hand side describes the NPV of the ongoing rotation, and the second term describes a discounted bare land value for all future generations (rotations). In both Equation 2 and Equation 3, the NPV was assessed at stumpage, indicating standing sales. Thus, there was no need to include harvesting costs in the financial analysis.

Financial data

For assessing the NPVs, time series covering the latest ten years for both stumpage prices and silvicultural costs were applied. Both series were

deflated by the cost-of-living index (base year 1951:10 = 100, see Statistics Finland 2022) to attain values in real terms. Then, arithmetic averages for silvicultural costs and stumpage prices in real terms were calculated (presented in Table 2). The rationale of applying a ten-year time series was to capture several business cycles such that the average value would include both peak and bottom values for stumpage prices and silvicultural costs.

Optimisation

To find out the lowest cost for reducing greenhouse gas emissions and nutrient export, an optimisation framework was applied. Altogether there were eleven simulation stands (representing the miniature of the Kiiminkijoki catchment area; see Table 1 and Table 3) which could be managed according to either CCF or RF. There were three objective functions, of which the first one was:

$$MaxNPV_A = \alpha_n \sum_{n=1}^{11} NPV_{CCF}^n + \beta_n \sum_{n=1}^{11} NPV_{RF}^n \quad [4]$$

subject to

$$\alpha_n + \beta_n = 1 \mid \alpha, \beta \in \{0,1\} \quad [5]$$

where $MaxNPV_A$ is the maximum net present value (€) for the miniature A extending to 1,000 hectares;

Table 2. Stumpage prices (€ m⁻³) and costs (€ ha⁻¹) of silvicultural measures.

Measure	Species	Sawlogs (€ m ⁻³)	Pulpwood (€ m ⁻³)
First commercial thinning	pine	39.23	12.11
	spruce	40.68	11.93
	birch	32.75	11.84
Intermediate thinnings	pine	48.00	15.35
	spruce	48.82	15.77
	birch	37.03	14.76
Final felling	pine	56.68	18.19
	spruce	57.97	19.47
	birch	43.60	17.62
Forest management costs (€ ha ⁻¹)			
Clearing of a thinning area			194.17
Planting			706.18
Seeding			273.35
Mounding			411.62
Early cleaning			388.03
Pre-commercial thinning			464.41
Ditch network maintenance			241.72
Fertilisation			387.75



Table 3. Simulated management regimes under CCF and RF, for each peatland site type. In the case of RF, good condition of ditches at the onset of the simulation was assumed.

Simulation stand	CCF		RF	
	Conversion phase	Steady state	Ongoing ⁴⁾	Future ⁴⁾
Dwarf-shrub type average	15 :32.7 (8.5) ¹⁾ 45 : 41.6 (23.4) ²⁾	45 [30]:37.2 (16.0) ³⁾	48 : 65.6 (18.3) ⁴⁾ C56 :141.9 (60.5)	S16 :21.3 (15.7) C115 : 164.4 (30.1)
Dwarf-shrub type upper quartile	0 : 81.4 (36.6) 30 : 51.2 (28.0)	30 [30]:51.2 (28.0)	0 : 53.9 (12.8) C50 : 205.5 (103.4)	
<i>Vaccinium vitis-idaea</i> type II lower quartile	40 :53.3 (31.8)	40 [25]: 53.3 (31.8)	C48 : 221.2 (124.0)	
<i>Vaccinium vitis-idaea</i> type II average	10 : 55.8 (31.4) 35 : 61.8 (41.7)	35 [25]:58.8 (36.6)	24 :65.4 (30.0) C34 : 218.2 (143.7)	44 :49.3 (2.0) 56 :62.1 (13.4) C74 : 271.6 (182.0)
<i>Vaccinium vitis-idaea</i> type II upper quartile	0 : 97.9 (49.3) 20 : 55.5 (37.9)	20 [25]:51.3 (34.1)	0 : 64.2 (16.5) C20 : 217.3 (129.8)	
<i>Vaccinium myrtillus</i> type II lower quartile	30 :56.8 (31.7) 50 : 63.9 (43.5)	50 [20]:60.4 (37.6)	C40 :263.0(143.9)	
<i>Vaccinium myrtillus</i> type II average	5 :70.3 (42.9) 25 : 65.1 (42.1)	25 [20]:67.7 (42.5)	C26 :274.5(167.2)	39 :56.0(2.6) 51 :76.5(20.4) C67 :287.9(200.4)
<i>Vaccinium myrtillus</i> type II upper quartile	0 :114.3(62.1) 15 :67.8(43.0)	15 [20]:64.7(40.0)	0 :71.9(23.5) C17 :149.0(138.0)	
<i>Vaccinium vitis-idaea</i> type II average	5 :52.8(19.6) 25 :50.8(28.2)	25 [25]:54.4(32.1)	17 :55.5(20.2) C32 :153.6(65.8)	46 :60.1(3.3) 64 :85.9(42.5) C89 :362.8(314.3)
<i>Vaccinium myrtillus</i> type II average	0 :62.9(26.1) 20 :62.6(37.4)	20 [20]:57.2(2.9)	13 :71.7(25.8) C25 :226.3(137.2)	36 :51.9(0.3) 52 :86.4(37.9) C80 :405.7(349.8)
Herb-rich type average	0 :59.9(27.0) 15 :56.0(24.3)	15 [20]:55.3(25.9)	9 :63.7(12.1) C24 :193.0(164.3)	35 :54.1(0.1) 47 :119.2 (90.6) C68 :352.3(307.2)

¹⁾Bold value **15** indicates the timing of the first felling operation during the conversion phase expressed in years from the start of the simulation, then the following value 32.7 shows the removal by felling ($\text{m}^3 \text{ha}^{-1}$), and the value in parenthesis (8.5) represents sawlog removal; ²⁾bold value **45** represents the timing of the second felling operation during the conversion phase, so the following value 41.6 represents removal by felling ($\text{m}^3 \text{ha}^{-1}$) and the value in parenthesis (23.4) corresponds to the removal of sawlogs; ³⁾bold value **45** indicates the time when the steady state begins expressed in years from the start, the value in square brackets [30] shows the felling cycle of the steady state in years, the following value 37.2 indicates removal by felling ($\text{m}^3 \text{ha}^{-1}$), and the value in parentheses (16.0) is sawlog removal; ⁴⁾“Ongoing” refers to the present tree generation and “Future” to all generations following the present generation, so the bold value **48** indicates the timing of thinning (in years) and the bold term **C56** refers to the year when clearfelling occurs, in the ongoing rotation, then the value 65.6 represents removal by felling and the value in parenthesis (18.3) indicates sawlog removal ($\text{m}^3 \text{ha}^{-1}$). Note that **S16** denotes natural regeneration, so self-seeded trees are removed at year 16 after the start of the simulation.

NPV_{CCF} and NPV_{RF} are calculated according to Equations 1 and 2, respectively; and α and β are binary decision variables such that, for each n , when $\alpha = 1$, then $\beta = 0$, and *vice versa*. In other words, only one management regime (either CCF or RF) is chosen for each simulation stand n in the optimum solution (note that each simulation stand n has a different area in hectares, see Table 1). The eleven simulation stands (see Table 1) constitute the miniature so that $\sum_{n=1}^{11} a_n = A$ (i.e., 1,000 hectares). Then, the second objective function describes the GHG emissions to be minimised:

$$MinGHG_A = \alpha_n \sum_{n=1}^{11} GHG_{CCF}^n + \beta_n \sum_{n=1}^{11} GHG_{RF}^n \quad [6]$$

where $MinGHG_A$ (t CO₂) is the minimum GHG emission for the miniature A (1,000 hectares), the same constraint (Equation 5) applies as for the $MaxNPV_A$ objective function (Equation 4), and GHG_{CCF} and GHG_{RF} refer to GHG emissions when CCF or RF is applied. The third objective function represents the nutrient export to be minimised:

$$MinNE_A = \alpha_n \sum_{n=1}^{11} NE_{CCF}^n + \beta_n \sum_{n=1}^{11} NE_{RF}^n \quad [7]$$

where $MinNE_A$ is the minimum nutrient export NE (kg) for the miniature A (1,000 hectares), the same constraint (Equation 4) applies as for $MaxNPV_A$, and NE_{CCF} and NE_{RF} refer to nutrient export associated with CCF and RF, respectively.

Since the optimisation problem was relatively simple, a spreadsheet (Microsoft 365 Apps for enterprise) routine incorporated with Solver application (Microsoft Visual Basic for Applications, ver 7.1) was constructed for solving the problem. Equations 4, 6 and 7 were solved first, then a proportion was constructed to calculate a trade-offs between NPV and GHG emissions and NPV and NE for each case k , $k = 1 \dots K$. For instance, for each case k , $MaxNPV_A$ is associated with GHG emissions of \bar{c}_{MaxNPV_A} and $MinGHG_A$ is associated with a NPV value of $\overline{NPV}_{MinGHG_A}$. The proportion used to calculate the trade-off between NPV and CO₂ emissions for case k (TO_k ; expressed in € tCO₂⁻¹) is simply:

$$TO_k = \frac{MaxNPV_A - \overline{NPV}_{MinGHG_A}}{|MinGHG_A - \bar{c}_{MaxNPV_A}|} \quad [8]$$

where is trade-off between financial value and greenhouse gas emissions for case k . Different cases $k = 1 \dots K$ correspond to alternative interest rates (2 %, 3 % or 4 %) and the inclusion or exclusion of

soil carbon. A trade-off between financial value and nutrient export was assessed accordingly. When interpreting the trade-off results it should be borne in mind that the NPV values (nominator in Equation 8) are generated from an infinite time horizon (Equations 2 and 3) whereas the GHG emissions and nutrient export (denominator in Equation 8) represent a fixed time horizon of 50 years. This discrepancy of timespans prevents generalisation of the results. However, the results can be compared with other results for similar conditions.

RESULTS

Total yield and felling removals

Total yield associated with RF tended to be higher than that associated with CCF (Table 4). For instance, total yield associated with a 50-yr simulation period (plus accumulated yield corresponding to initial stands before simulation) was 335.8 m³ ha⁻¹ for RF and 275.4 m³ ha⁻¹ for CCF (Table 4), indicating a difference between RF and CCF of approximately 22 %. Regarding felling removals associated with a 50-year simulation period, RF outperformed CCF by as much as 77 % (255.6 m³ ha⁻¹ versus 144.3 m³ ha⁻¹; Table 4). With a 20-year simulation period the differences between CCF and RF were considerably smaller; for instance, total felling removal was 73.4 m³ ha⁻¹ under CCF and 75.9 m³ ha⁻¹ under RF (Table 4). However, the difference in total yield between RF and CCF was similar to that for the 50-year simulation period, at around 26 % (231.9 m³ ha⁻¹ versus 184.3 m³ ha⁻¹; Table 4).

Net present values, NPVs

The NPVs associated with RF and CCF are presented in Table 5. On average, RF resulted in higher NPVs compared to CCF, but CCF outperformed RF in nutrient-poor peatland sites (dwarf-shrub type) and with high interest rates (Table 5). At stand level RF outperformed CCF by 16–45 %, depending on the interest rate (Table 5).

Greenhouse gas balance and nutrient export

The greenhouse gas balance and nutrient export for the 50-year period are presented for each simulation stand associated with RF and CCF management, in Table 6. RF tended to result in higher GHG emissions and NE export than CCF on average, but there were considerable fluctuations amongst the peatland site types (Table 6). For instance, *Vaccinium vitis-idaea* type II (average) was a notable GHG source under RF management and a GHG sink under CCF management (Table 6). On the other hand, RF

Table 4. Total yield and removals by felling associated with CCF and RF, when stand growth was simulated for 20 or 50 years from the initial stands. Grey-shaded site types represent pine mires, while spruce mires are presented without shading. For RF, good condition of ditches is assumed at the onset of simulations. Note that the 20-year time period is included here for comparison only - the 50-year period was applied for both greenhouse gas emissions and nutrient loading.

Management system	Continuous cover forestry (CCF)			Rotation forestry (RF)		
	Yield (m ³ ha ⁻¹)	Removal by felling (m ³ ha ⁻¹)		Yield (m ³ ha ⁻¹)	Removal by felling (m ³ ha ⁻¹)	
		total	sawlogs		total	sawlogs
Dwarf-shrub type average	126.7 ¹⁾ 183.7	32.7 74.3	8.5 32.0	141.7 220.0	0.0 65.6	0.0 18.3
Dwarf-shrub type upper quartile	204.0 259.0	81.4 132.6	36.6 64.5	218.6 284.3	53.9 259.3	12.8 116.3
<i>Vaccinium vitis-idaea</i> type II lower quartile	80.3 194.0	0.0 53.3	0.0 31.8	99.9 244.8	0.0 221.2	0.0 124.0
<i>Vaccinium vitis-idaea</i> type II average	175.0 275.7	55.8 117.6	31.4 73.1	231.8 332.2	0.0 283.6	0.0 173.6
<i>Vaccinium vitis-idaea</i> type II upper quartile	246.2 327.0	153.3 200.5	87.1 117.5	292.7 354.1	281.6 281.6	146.2 146.2
<i>Vaccinium myrtillus</i> type II lower quartile	115.4 236.7	0.0 120.7	0.0 75.2	149.5 298.0	0.0 263.0	0.0 143.9
<i>Vaccinium myrtillus</i> type II average	210.0 311.8	70.3 135.5	42.9 85.0	271.9 372.3	0.0 274.5	0.0 167.2
<i>Vaccinium myrtillus</i> type II upper quartile	288.3 375.7	182.2 243.7	105.1 142.2	327.3 452.9	308.7 308.7	168.6 168.6
<i>Vaccinium vitis-idaea</i> type II average	176.4 256.1	52.8 161.5	19.6 83.8	237.8 323.4	55.5 263.3	20.2 156.9
<i>Vaccinium myrtillus</i> type II average	209.4 287.5	62.9 177.3	26.1 94.9	284.2 383.7	71.7 298.0	25.8 163.0
Herb-rich type average	195.7 322.0	115.9 170.4	51.3 78.9	295.4 428.2	63.7 311.0	12.1 176.4
Arithmetic average²⁾	184.3 275.4	73.4 144.3	37.1 79.9	231.9 335.8	75.9 257.3	35.1 141.3

¹⁾Upper values are for 20-year and lower line for 50-year simulation period, note that yield indicates total yield at the simulation year 20 or 50 including the yield accumulated before the initial stand is fed into the Motti stand simulator (values are comparable since identical initial stands were used for both CCF and RF simulations - see Table 1; ²⁾for simplicity, arithmetic average (rather than area-weighted average) was calculated.

produced significantly lower greenhouse gas emissions than CCF for the dwarf-shrub stand type (upper quartile). With regard to nutrient export, RF introduced more loading than CCF without exception, i.e., for all peatland site types (Table 6).

Trade-offs between NPV, greenhouse gas balance and sediment and nutrient export

The optimal solutions spanned both management systems (RF and CCF) for every objective function except MinNE (minimising nutrient export), for

which CCF management was always chosen (Table 7). For the MaxNPV (maximising net present value) objective function, RF was selected for nine of the eleven peatland site types and CCF outperformed RF only in the Dwarf-shrub site type (Table 7). An interesting outcome was that, in general, CCF was chosen when the objective function was to minimise greenhouse gas emissions including soil emissions. The two exceptions to that rule represented the site type with the lowest nutrient status, i.e., Dwarf-shrub type (Table 7).

Table 5. NPVs (€ ha⁻¹) associated with RF (upper values) and CCF management (lower values) at interest rates of 2 %, 3 % and 4 %. Bold values indicate cases where CCF emerges as the superior management approach.

Simulation stand	2 %	3 %	4 %
Dwarf-shrub type average	1905.8 1810.8	1130.3 1112.6	701.8 773.0
Dwarf-shrub type upper quartile ⁴⁾	3950.4 4705.2	2743.0 3700.1	2064.5 3229.7
<i>Vaccinium vitis-idaea</i> type II lower quartile	4393.6 2393.5	2255.7 1184.8	1298.4 661.4
<i>Vaccinium vitis-idaea</i> type II average	7023.9 4642.9	4355.1 3032.4	2976.8 2237.9
<i>Vaccinium vitis-idaea</i> type II upper quartile	8991.0 6859.9	6482.0 5395.5	5197.7 4674.3
<i>Vaccinium myrtillus</i> type II lower quartile	6257.7 2393.5	3395.5 1184.8	2070.6 661.4
<i>Vaccinium myrtillus</i> type II average	8890.8 7265.9	5627.9 4957.6	3968.2 3822.9
<i>Vaccinium myrtillus</i> type II upper quartile	10998.3 8689.5	7890.4 6912.2	6341.6 6024.9
<i>Vaccinium vitis-idaea</i> type II average	7438.8 4432.8	4419.6 3015.1	3012.5 2318.6
<i>Vaccinium myrtillus</i> type II average	9533.0 6487.1	5851.8 4608.8	4156.6 3694.0
Herb-rich type average	11742.6 5972.1	7096.7 4390.8	4949.8 3611.7

The trade-offs between minimal GHG emissions, minimal nutrient export and maximal NPV were assessed according to Equation 8. Table 7 illustrates the optimal solution for each objective function. Figure 3 shows the cost of GHG emission reduction (based on the trade-off calculation according to Equation 8), with and without soil emissions. The outcome was that the cost is practically identical, whether soil emissions are included or not (Figure 3). The difference was < 2 % depending on the interest rate applied. This was due to differences in soil GHG emissions between RF and CCF, which were minor compared to the differences in tree stand biomass. In practical terms, the cost of GHG emission relates to comparisons between situations where a forest owner maximises the NPV or, alternatively, minimises the GHG emissions; when choosing the latter, the forest owner loses money but reduces GHG emissions. Then, the cost of GHG emissions is the loss in NPV weighed against the reduction of GHG emissions.

When considering the cost of NE nutrient export expressed in € kg⁻¹, we found a considerably higher sensitivity to interest rate compared to the cost of CO₂

emissions (Figure 4 versus Figure 3). For instance, with a 2 % interest rate, the cost of NE nutrient export exceeded € 58 kg⁻¹, while with a 4 % interest rate this cost decreased to less than € 17 kg⁻¹ (Figure 4).

Sensitivity analysis

Since the original analyses were conducted over a 50-year time period, a new set of optimisations was executed for the 20-year time period (Figure 5). The costs of reducing GHG emissions and nutrient export were higher with the 20-year time period than with the 50-year period, particularly for reducing nutrient export (Figure 5). This outcome can be simply explained by the fact that less improvement (in terms of reduction) can be achieved during a shorter time period, while the financial performance is kept intact (see Equations 4 and 8).

Furthermore, the time period significantly influenced the GHG balance and nutrient export, as fewer felling operations occurred when the study was limited to the first 20 years. Especially, there were fewer final fellings under RF management. As a result, RF led to lower GHG emissions than CCF

Table 6. Greenhouse gas emissions with and without soil emissions (i.e., only living biomass) and nutrient loading associated with RF and CCF management. Negative greenhouse gas emissions indicate sinks, positive ones indicate sources. Nitrogen equivalents (NE) are the summed loads of nitrogen and phosphorus where phosphorus and nitrogen loads are measured jointly in terms of their effects in causing eutrophication. All values are sums for the 50-yr time period.

Simulation stand	CO ₂ -eq GHG emissions (t ha ⁻¹)		NE Nutrient export (kg ha ⁻¹)	
	RF	CCF	RF	CCF
Dwarf-shrub type average	-66.02 (-47.00) ¹⁾	-45.32 (-21.63)	84.46	76.65
Dwarf-shrub type upper quartile	-53.54 (-34.69)	73.31 (98.98)	83.56	69.60
<i>Vaccinium vitis-idaea</i> type II lower quartile	35.63 (39.83)	-98.81 (93.80)	108.97	94.30
<i>Vaccinium vitis-idaea</i> type II average	110.37 (107.19)	-19.00 (-21.63)	166.19	121.60
<i>Vaccinium vitis-idaea</i> type II upper quartile	174.13 (183.02)	96.11 (98.98)	127.89	105.16
<i>Vaccinium myrtillus</i> type II lower quartile	237.44 (46.57)	77.29 (-123.67)	170.62	116.52
<i>Vaccinium myrtillus</i> type II average	312.99 (123.02)	199.39 (1.26)	173.46	119.66
<i>Vaccinium myrtillus</i> type II upper quartile	354.59 (172.70)	333.64 (121.39)	142.81	140.05
<i>Vaccinium vitis-idaea</i> type II average	116.73 (133.07)	34.83 (44.15)	140.14	113.70
<i>Vaccinium myrtillus</i> type II average	288.64 (138.25)	233.04 (51.59)	144.52	124.64
Herb-rich type average	175.97 (-0.91)	199.06 (-0.98)	163.89	123.39
Arithmetic average²⁾	129.38 (63.42)	90.70 (6.21)	128.88	103.69

¹⁾values in parentheses represent greenhouse gas emissions of only living biomass, i.e., without soil emissions;

²⁾for simplicity, arithmetic average was applied instead of area-weighted average (see text below Table 4).

during the 20-year time period in most cases (Table 8), which is a reversal of the findings from analysis of the 50-year time period (see Table 6). Nutrient export was still lower in CCF compared to RF during the first 20 years, although the difference was relatively small (Table 8).

DISCUSSION

Peatlands provide a variety of ecosystem services worldwide (Juutinen *et al.* 2020a). Ecosystem services such as climate change mitigation and biodiversity conservation require actions which are directly linked to decisions on how to manage

peatland forests. Furthermore, trade-offs between timber production and, e.g., carbon sequestration need to be revealed for successful multipurpose land management. Eyvindson *et al.* (2023) have recently suggested that there could be a wide range of management alternatives for drained peatland forests that contribute positive economic benefits while being reasonable in terms of managing ecosystem GHG balance. However, to date there have been no studies tackling the trade-offs between financial performance (NPV), nutrient export and greenhouse gas balance in the context of exercising free choice between CCF and RF in drained peatland forests (cf. the contribution of Juutinen *et al.* 2020a in which only RF was considered). This study fills that knowledge gap.

Table 7. Optimal solutions for each objective function. Symbol “X” indicates that RF, and symbol “Δ” that CCF was chosen in the optimal solution for a particular simulation stand.

Simulation stand	Objective function					
	MinGHG		MinNE ²⁾	MaxNPV		
	with ¹⁾	without		2 %	3 %	4 %
Dwarf-shrub type average	X	X	Δ	X	X	Δ
Dwarf-shrub type upper quartile	X	Δ	Δ	Δ	Δ	Δ
<i>Vaccinium vitis-idaea</i> type II lower quartile	Δ	X	Δ	X	X	X
<i>Vaccinium vitis-idaea</i> type II average	Δ	X	Δ	X	X	X
<i>Vaccinium vitis-idaea</i> type II upper quartile	Δ	X	Δ	X	X	X
<i>Vaccinium myrtillus</i> type II lower quartile	Δ	X	Δ	X	X	X
<i>Vaccinium myrtillus</i> type II average	Δ	Δ	Δ	X	X	X
<i>Vaccinium myrtillus</i> type II upper quartile	Δ	X	Δ	X	X	X
<i>Vaccinium vitis-idaea</i> type II average	Δ	X	Δ	X	X	X
<i>Vaccinium myrtillus</i> type II average	Δ	X	Δ	X	X	X
Herb-rich type average	Δ	X	Δ	X	X	X

¹⁾“with” indicates that soil emissions are included in greenhouse gas (GHG) emissions, and “without” refers to GHG emissions of living biomass only; ²⁾MinNE corresponds to the objective function to minimise sediment and nutrient loading.

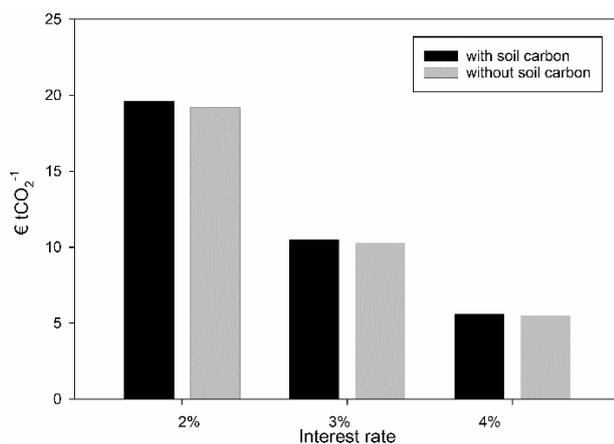


Figure 3. Cost of greenhouse gas emission reduction with and without soil emissions according to the optimisation for a 50-year period.

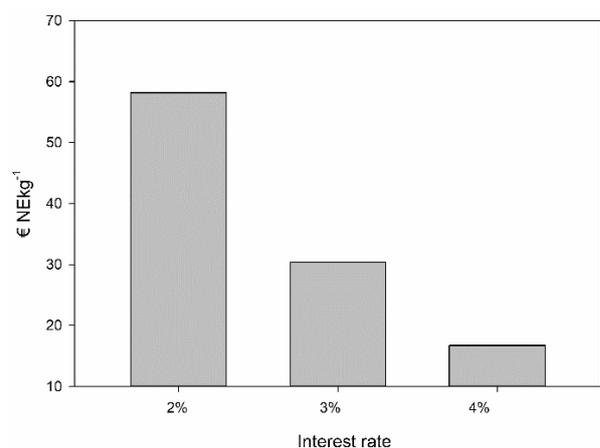


Figure 4. Costs (€ kg⁻¹) of reducing NE nutrient export with alternative interest rates, according to the optimisation for a 50-year period.



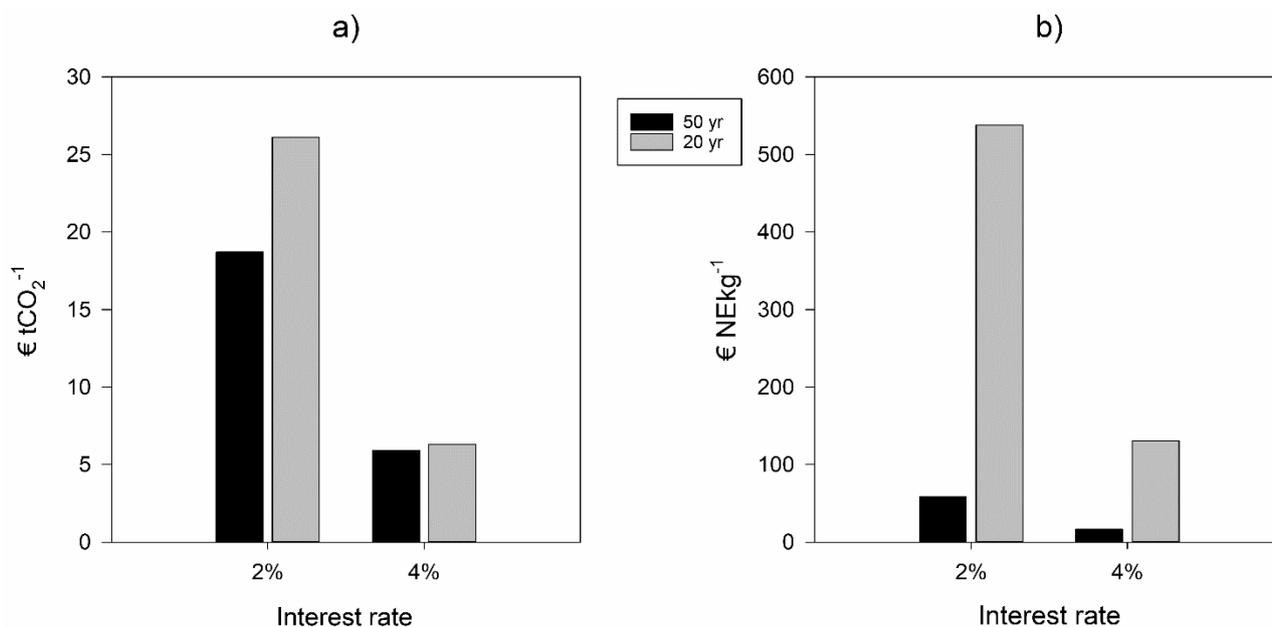


Figure 5. Cost of greenhouse gas emission reduction (a) and cost of reducing nutrient export (b) with 50-year and 20-year time periods. Interest rates 2 % and 4 %. Greenhouse gas emission reductions included soil carbon. Note that the black bars are identical to the corresponding bars presented in Figure 3 and 4.

Current literature focusing on stand-level optimisation in mineral-soil forests tends to impose a restricting forest management strategy whereby the optimal solution favours either CCF or RF (to name a few recent articles, Parkatti *et al.* 2019, Parkatti & Tahvonen 2021, Parkatti *et al.* 2023). Although the division at stand level holds (i.e., the forest owner chooses either RF or CCF), at landscape level the situation is different: optimal forest management might entail a solution involving both RF and CCF (Eyvindson *et al.* 2021). Of course, this depends on the objective function as well as on the forest structure in question (Eyvindson *et al.* 2021). Furthermore, both management systems (RF and CCF) have their benefits. For instance, CCF causes less soil disturbance (Laudon & Hasselquist 2023) and generates milder detrimental impacts than RF on ecosystem services provided by peatlands (Nieminen *et al.* 2018b), while RF produces more timber per unit area (Tahvonen & Rämö 2016, Hynynen *et al.* 2019, Bianchi *et al.* 2020). At landscape level the ultimate question is how to gain the most benefits from both management systems, RF and CCF.

In this study the optimal solution was free of management restrictions, i.e., both RF and CCF management systems could be included. This approach is identical to the approach adopted by Eyvindson *et al.* (2021), and generally enables a considerably larger solution space for optimisation - let alone the fact that it makes forest management versatile and thus contributes multifunctionality

(Peura *et al.* 2018, Eyvindson *et al.* 2021). The landscape was a miniature (1,000 ha) of an existing large catchment area with forest data representing Scots pine dominated drained peatland stands. Our focus was on stands dominated by Scots pine because they constitute over 70 % of the forestry drained peatland sites in northern Finland, whereas the proportion of stands dominated by Norway spruce is less than 20 % (Korhonen *et al.* 2017). The results of this study demonstrate that the cost of reducing GHG emissions (i.e., the cost of C abatement, see Assmuth *et al.* 2018 for definition) ranges between ~5 and 20 € tCO_2^{-1} , depending on the interest rate applied (2 %, 3 % or 4 %). These values are low compared to the recent clearing prices at auctions of carbon in the European Union Emissions Trading System (EU ETS) (EU carbon permits; see <https://tradingeconomics.com/commodity/carbon>).

Furthermore, the values are well below the global social cost of carbon (SCC) presented by Ricke *et al.* (2018). SCC is a widely employed metric for the expected economic damage from CO_2 emissions, and the global median SCC is estimated to be US\$ 417 which corresponds to about € 383 (ECB 2023) per t of CO_2 (but note that the 66 % lower confidence interval lies at US\$ 177 corresponding to about € 163 per t of CO_2 ; see Ricke *et al.* 2018). Thus, in our case-study area it would be very cost-efficient and beneficial for society to sequester carbon. In addition, future carbon prices are likely to rise rather than decline (e.g., Hintermayer 2020) which improves

Table 8. Greenhouse gas (GHG) emissions including soil emissions and nutrient export associated with RF and CCF management for a 20-yr time period. Negative greenhouse gas emissions indicate sinks, positive ones indicate sources. Nitrogen equivalents (NE) are the summed loads of nitrogen and phosphorus where phosphorus and nitrogen loads are jointly measured in terms of their effects causing eutrophication.

Simulation stand	CO ₂ -eq GHG emissions (t ha ⁻¹)		NE nutrient export (kg ha ⁻¹)	
	RF	CCF	RF	CCF
Dwarf-shrub type average	-53.68	-19.96	29.20	31.52
Dwarf-shrub type upper quartile	19.17	37.98	29.79	25.03
<i>Vaccinium vitis-idaea</i> type II lower quartile	-64.54	-60.89	24.60	26.71
<i>Vaccinium vitis-idaea</i> type II average	-75.72	-9.78	48.49	49.17
<i>Vaccinium vitis-idaea</i> type II upper quartile	-23.15	47.97	48.68	39.97
<i>Vaccinium myrtillus</i> type II lower quartile	-10.30	-0.20	36.06	39.91
<i>Vaccinium myrtillus</i> type II average	-2.26	74.41	51.52	49.86
<i>Vaccinium myrtillus</i> type II upper quartile	353.54	224.30	73.69	48.84
<i>Vaccinium vitis-idaea</i> type II average	-28.35	-13.68	46.01	40.97
<i>Vaccinium myrtillus</i> type II average	57.69	68.67	58.22	45.86
Herb-rich type average	39.81	139.54	59.31	50.20
Arithmetic average¹⁾	13.66	36.92	45.47	38.11

¹⁾For simplicity, arithmetic average was applied instead of area-weighted average (see text below Table 4).

the economic feasibility presented here. The inclusion of soil GHG emissions into the assessments of this study changed the cost of GHG emission reductions by a minuscule amount. This result contradicts the outcome of another recent study (Parkatti *et al.* 2023), but one should bear in mind that our study tackled landscape level assessments while Parkatti *et al.* (2023) focused on stand-level analyses. Also, Parkatti *et al.* (2023) conducted their analyses on mineral soil and with pure Norway spruce stands while our study focused on Scots pine - dominated stands on drained peatlands. However, our result (no considerable difference in the cost of greenhouse gas emissions whether soil emissions are included or omitted) is worth testing with larger datasets incorporating other tree species and geographical locations, and alternative sets of initial stand data.

According to the EU Water Framework Directive (WFD 2000), efficient mitigation measures to

improve the quality of water discharging from drained peatland forests are urgently called for (Nieminen *et al.* 2022). Given that drained peatland forests have been shown to be more significant sources of nutrients than undrained pristine peatlands (Finer *et al.* 2021), it is logical to prioritise drained peatland forest areas for action. Additionally, Continuous Cover Forestry (CCF) on peatlands tended to contribute less nutrient export than Rotation Forestry (RF) in this study (Table 6), as also reported by, e.g., Nieminen *et al.* 2018b and Sarkkola *et al.* 2021). However, at the same time the losses in NPV associated with CCF (see Table 5) were notable, resulting in an optimal solution in which the cost of reducing NE nutrient export turns out to be high (ranging from about € 17 to € 58 kg⁻¹) when compared to literature values from mineral soil sites where the reducing cost of CCF has been on average € 8 kg⁻¹ (Gren 2001). One reason for the discrepancy

between earlier studies and our study is that earlier studies report cleaning/purifying costs while we assessed the cost of reducing nutrient export through optimisation with the corresponding opportunity cost, i.e., loss of NPV (see Equation 7). Nevertheless, according to our results, reducing nutrient export tends to be somewhat expensive, indicating that alternative measures (Nieminen *et al.* 2017, Nieminen *et al.* 2018b) - other than applying CCF - might be more cost-effective.

To avoid misinterpretations of the results it should be stressed that the financial performance (here NPV) associated with CCF is highly dependent on the initial state of a stand, especially the size distribution of trees (e.g., Juutinen *et al.* 2020b). In this study the initial stands were derived from openly available data representing young and advanced thinning stands well before maturity. In that respect the results are *ad hoc* and conditional on the initial stand structures. Furthermore, it seems that the initial stand structure favours RF in economic terms. On the other hand, the initial stands were identical for both RF and CCF systems. One can argue that the dataset here is a valid representation of existing Scots pine - dominated forests on drained peatlands located in northern Finland (see Korhonen *et al.* 2017). Another apparent constraint of this study is the fact that GHG emissions and nutrient export were assessed for a fixed time period of 50 years whereas the financial performance (NPV) was calculated to infinity. This creates a slight discrepancy which limits the generalisability of our results. On the other hand, a sensitivity analysis spanning an alternative time period (20 years) was conducted indicating that the results vary substantially between different time periods. Thus, the temporal element is crucial. However, the results of this study serve as a first attempt to evaluate trade-offs between financial performance and ecosystem services on drained peatlands.

When it comes to sustainable forest management with multifunctionality, the bottom line is to be able to quantify trade-offs between multiple benefits of entire forest landscapes (Makrickas *et al.* 2023). This study demonstrated that combining CCF and RF - rather than restricting forest management to focus on either RF or CCF only - would result in the best solutions for cost-effective reduction of greenhouse gas emissions and nutrient export in drained Scots pine - dominated peatland forests in northern Finland. At the same time, however, the results were divaricated: the costs of reducing greenhouse gas emissions through combining RF and CCF were very low while the costs of reducing nutrient export tended to be much higher than reported so far. Thus, further studies on the subject are called for.

AUTHOR CONTRIBUTIONS

AA originated and planned the work, wrote the first draft, is the corresponding author, and is responsible for the Motti simulations for RF, optimisation and financial analyses; JR is responsible for the Motti simulations for CCF and commented on the draft; HH provided guidance for building the calculation framework and commented on the draft; SS is responsible for the sediment and nutrient export assessments and commented on the draft; PO is responsible for the greenhouse gas emission calculations and commented on the draft; SH is responsible for building the bridge between Motti and SUSI simulators and commented on the draft; LS is responsible for building the bridge between SUSI and Motti simulators, calculated the average WT and commented on the draft; AJ helped in designing the financial calculation (NPV) and optimisation frameworks, and commented on the draft.

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Author for correspondence: Anssi Ahtikoski, Principal Scientist, Natural Resources Institute Finland (Luke), Tekniikankatu 1, FIN-33720 Tampere, Finland. Tel: +358 50 391 4416; E-mail: anssi.ahtikoski@luke.fi

