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Costs and benefits of implementing continuous cover forestry in boreal peatlands

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ABSTRACT

Climate change and forestry activities heighten the risk of nutrient export from boreal peatland forests into watercourses, threatening water quality. Recognizing a nutrient-reducing practice is insufficient; evaluating costs and benefits is crucial to choose the best options. This study addresses this gap by applying a cost-benefit analysis to continuous cover forestry (CCF) as a strategy to mitigate phosphorus (P) export. The NutSpaFHy model estimated P exports under different management scenarios, comparing rotation forestry (RF) with CCF. Key variables measured included P reduction, net present value, revenue losses, and consumer surplus from recreation. Results showed CCF reduced P exports to 0.022 kg/ha/year, roughly one-third of RF levels on sites suitable for CCF. Recreational benefits, quantified at 6.55€/person/year/kg, were assessed using travel cost and contingent behavior valuation methods. Revenue impacts were evaluated using a size-structured forest optimization model, with CCF costs determined by revenue differentials between optimal management and immediate CCF conversion. High discount rates and mesic sites favor CCF as the optimal solution, indicating no additional costs from an immediate switch on mature stands. Analysis across discount rates (1%, 3%, and 5%) suggests CCF is a viable water protection option, meeting cost-benefit criteria with a benefit-cost ratio of 4.05.

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Introduction

The increased export of nutrients from surrounding terrestrial ecosystems into water courses poses an emerging risk in boreal catchments due to the changing climate (Pörtner et al. 2022). This problem is pronounced in boreal peatland forests, which cover approximately 249.5 million hectares globally (Leifeld and Menichetti 2018) and serve as significant potential sources of nutrients (Nieminen et al. 2017). In Finland, peatlands account for a quarter of the total forest land area, altogether 9.08 million hectares, about half of which have been drained for forestry purposes (Päivänen and Hännell 2012; Natural Resources Institute Finland 2023). Forest management practices, such as harvesting, regeneration cutting, and ditching increase the export of nutrients, suspended solids, and organic carbon into nearby water courses (Nieminen et al. 2017; Leifeld and Menichetti 2018). For the European boreal region, climate change scenarios predict increasing temperatures and precipitation and decreasing numbers of frost days during the winters (Mikkonen et al. 2015; Ruosteenoja et al. 2016; Pörtner et al. 2022), all of which may increase the export of nutrients (Salmivaara et al. 2023). Higher concentrations of nutrients and organic matter promote eutrophication, algal blooming, the presence of blue-green algae, and reduce water clarity (brownification). These

changes in water quality reduce the provision of ecosystem services in inland waters (Lankia et al. 2019). Consequently, the value attributed to the water quality, i.e. the usability of the water and aquatic environments, such as number of recreational visits and the monetary value of recreation activities is expected to decrease (Ahtiainen et al. 2015; Lankia et al. 2019; Bertram et al. 2020). Given these risks, there is a pressing need for effective adaptation measures in forest management, and assessing their cost-effectiveness is crucial to ensure sustainable and economically viable solutions.

Rotation-based forestry (RF) is the prevalent management regime on peatlands in Finland (Päivänen and Hännell 2012). The most essential management practices affecting the amount and growth of tree stands include intermediate thinning, regeneration harvestings through clear-felling, and ditch network maintenance (DNM) which is a commonly used method to improve drainage conditions and promote tree growth, as ditch conditions gradually deteriorate over time, reducing their drainage capacity and has been shown to sustain and enhance forest growth, thereby increasing timber revenues. DNM is implemented during the rotation and as part of site preparation after harvesting to mitigate the rise in the water table caused by the removal of evapotranspiring biomass and to promote regeneration. However,

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it can also have negative impacts, such as increasing the concentration of suspended solids, dissolved organic carbon, and nutrients in runoff water (Joensuu et al. 2001).

Field studies indicate that implementing continuous cover forestry (CCF) on peatlands can reduce nutrient and sediment export, regulate water tables, and decrease the need for DNM (Nieminen et al. 2018; Leppä et al. 2020). Although DNM may still be necessary in CCF, it is required less frequently than in RF (Nieminen et al. 2018; Juutinen et al. 2021). Studies have argued that CCF, by promoting mixed-species, uneven-aged stand structures, may provide greater resilience to various forest disturbances, such as wind damage, compared to RF (O'Hara and Ramage 2013; Hanewinkel et al. 2014; Knoke et al. 2022; Mohr et al. 2024) and promote biodiversity (Joelson et al. 2017). Furthermore, CCF has been argued to have high multifunctionality properties compared to rotation forestry (RF), such as bilberry production and scenic beauty (Peura et al. 2018). In fertile peatland forests, CCF is suggested to be better in terms of carbon sequestration (Lehtonen et al. 2023). Recent studies suggest that CCF can be economically and socially more favorable than RF on peatlands (Nieminen et al. 2018) due to its less intensive DNM and site preparation investment requirements and reduced externalities due to smaller greenhouse gas (GHG) emissions and export loads of suspended solids, dissolved carbon, and nutrients (Juutinen et al. 2021).

A review of analytical economic models focusing on forest management highlighted a research gap concerning the negative externalities associated with DNM (Ollikainen 2016). While Miettinen et al. (2020) have presented a model for mitigating the export of nutrients with buffer zones, sedimentation ponds, and overland flow fields, to the best of our knowledge, this study is the first to quantify the economic impacts of CCF in the context of phosphorus (P) export mitigation in boreal peatland forests. Past economic research on CCF has largely focused on its profitability in comparison to RF in terms of timber revenues. Recently, studies have included externalities such as carbon sinks (Assmuth and Tahvonen 2018; Parkatti et al. 2023) and negative externalities of forestry concerning reindeer husbandry in indigenous Sámi regions (Parkatti and Tahvonen 2021). From a societal perspective, merely recognizing that a management practice can reduce the export of nutrients is insufficient. It is imperative to evaluate the costs and benefits of various approaches, enabling policymakers to choose the most effective options. The seminal report by Dasgupta (2021) emphasizes that relying solely on market-based monetary measures of economic success results in unsustainable economic growth and advocates for consideration of a more diverse set of assets: produced, human, and natural capital.

The objective of this study was to evaluate the economic potential of CCF in mitigating P export by comparing the nutrient export impacts of CCF and RF within a sub-catchment of Lake Puruvesi, located in Southwestern Finland and representing an important recreational area. The forest management was modeled at the sub-catchment level, and the impacts were summarized over the larger Savonlahti Bay area to capture the broader effects on nutrient export and recreational values. We focused conversion of mature,

spruce-dominated stands on herb-rich and mesic sites as they are the next stands to contribute to export levels and due to their suitability for CCF for tree growth and natural regeneration (Nieminen et al. 2018). We used a novel interdisciplinary modeling system within the framework of societal Cost–Benefit Analysis (CBA), where the monetary impacts of changes in P exports were estimated for the recreational experiences of residents and visitors in the Savonlahti Bay area at the study site. The costs of transitioning to CCF were evaluated using a dynamic optimization model by maximizing the NPV of sample stands and comparing this unrestricted NPV to the optimization of NPV where clearcuts are restricted. A detailed Monte Carlo analysis was employed to analyze the model sensitivity to changes in parameter values, addressing uncertainty, and identifying threshold values leading to a net present value (NPV) break-even point. These monetized impacts, along with costs and benefits, were discounted over time and then compared and interpreted based on their expected NPV and benefit–cost ratio.

Study site

Our study focused on the sub-catchment of Vehka-Kuonanjärvi and the Savonlahti Bay of Lake Puruvesi (Figure 1), which together cover a land area of 9,700 ha. The forest management scenarios were modeled at the sub-catchment level (Figure 1, red hatched area). Water flows from shallow lakes via the Kuonanjoki River (Figure 1, blue dot) into the main body of Lake Puruvesi through Savonlahti Bay. Due to this spillover effect from the sub-catchment, the recreational impacts of P abatement were estimated for a larger area (Figure 1, area marked with a black line). Lake Kuonanjärvi suffers from internal loading, which is assumed to result from a long history of ditching in the peatlands (Hakala et al. 2021). The water areas in the study area are classified as having either a moderate or poor ecological status (FEI 2023). Lake Puruvesi is generally known for its excellent water quality. However, eutrophication and deterioration of water quality have emerged in the lake's shallow bay areas (Tossavainen, 2019; Hakala et al. 2021). For Lake Kuonanjärvi, a reduction target of 110 kg per year for P has been established, and approximately 8% of this target, or 8.8 kg per year, is allocated to forestry (Tattari and Leinonen 2017). The studied sub-catchment drains into the Savonlahti Bay, where the annual reduction target is estimated to be 200–300 kg, with 16–24 kg per year for forestry (Tossavainen, 2019). Approximately 89% of the sub-catchment land area is covered by forests (5,190 ha). Notably, 9% (477 ha) of this forest area is deemed suitable for CCF, as it consists of drained, nutrient-rich peatland sites covered by Norway spruce (*Picea abies* (L.) Karst) dominated forests, with Downy birch (*Betula pubescens* Ehrh.) as a common admixtural species.

Methods

A cost–benefit analysis approach was used, which integrated a system of three models (Figure 2) that compared

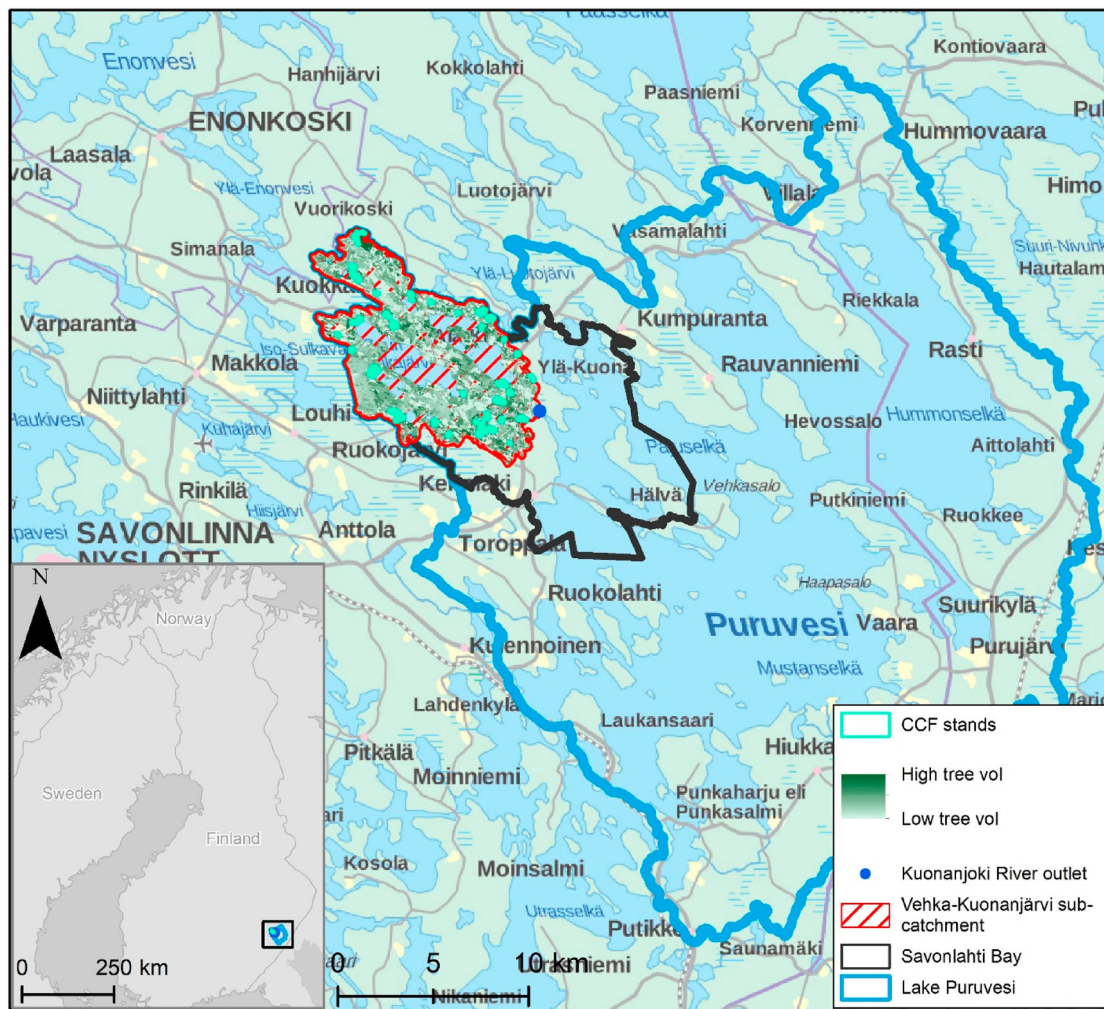


Figure 1. Study area overview. The red hatched area indicates the sub-catchment of Vehka-Kuonanjärvi (7,330 ha), the area of NutSpaFH simulations, and the black line shows the boundaries of the Savonlahti Bay (15,960 ha), the area of recreational impact assessment. The blue line delineates the main basin of Lake Puruvesi (101,600 ha). Data sources: FEI (2014), FFC (2018), base map from the National Land Survey of Finland.

the nutrient export impacts of CCF and RF in the study area. A spatially distributed nutrient export model called NutSpaFH (Laurén et al. 2021) was used to simulate the annual average of the total P exports from forested catchments for three different forest management scenarios: “No Harvests,” “RF,” and “CCF.” In the Vehka-Kuonanjärvi area, 76.3 ha were estimated to be suitable for CCF because the stands were dominated by mature Norway spruce trees with herb-rich (65.7 ha) or mesic (10.6 ha) fertility type peatland forests. We focused on mature stands as they are the next to be harvested, contributing significantly to the nutrient load. Additionally, previous economic research (Österberg et al. 2023) indicates that CCF can be economically more efficient than RF starting from bare land. While this suggests that CCF may already present an economically optimal solution for the younger stands in the 477 ha forest area suitable for CCF.

Total P export values were used as input for an economic evaluation of the recreational value of the water quality in the lake. The benefit estimations of the water quality improvements due to the reduced P exports were based on prior surveys and modeling covering the Savonlahti Bay area. The

monetized benefits from the better water quality were compared with the potential revenue losses for forest owners caused by the transition from RF to CCF. Revenue losses were estimated using an economic-ecological optimization model. We used a 16 m × 16 m gridded forest resource dataset intersecting with the stand data to simulate the initial states of two sample forests representing the two fertility classes, herb-rich and mesic, suitable for CCF in the optimization model. Revenue losses were calculated with 1%, 3%, and 5% discount rates and then aggregated across the forest stands in the Vehka-Kuonanjärvi area matching the sample forest fertility class.

Cost–benefit analysis

We used a CBA to assess the social benefits of CCF versus the potential revenue losses for forest owners, employing the nine-step framework presented by Boardman et al. (2017) (Figure 3). For the year 2023, all costs and benefits were expressed in euros. The benefits were adjusted using the Consumer Price Index (CPI) from the Official Statistics of Finland (OSF 2023a) and costs were adjusted using the Wholesale

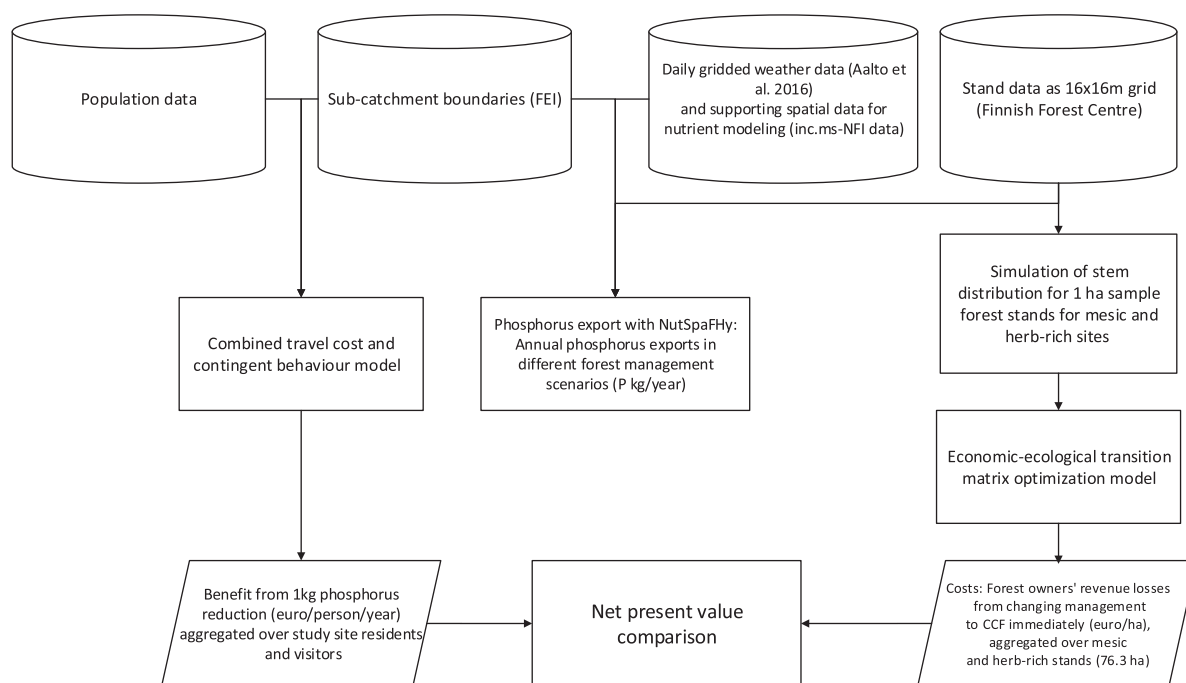


Figure 2. Data flow in the CBA modeling system.

Price Index (OSF 2023b). Future revenue and cost streams were discounted to present values over an infinite time horizon using discount rates of 1%, 3%, and 5%, with the 3% rate aligning with European Commission recommendations for developed EU countries (Sartori et al. 2014). The CBA results were presented in two metrics: the expected

net present value (NPV), indicating the net value of benefits minus costs, and the benefit–cost ratio (BCR). The key decision-making rule of CBA is that a positive NPV (BCR exceeding 1) indicates economic efficiency, as the project generates more social welfare than costs (Boardman et al. 2017).

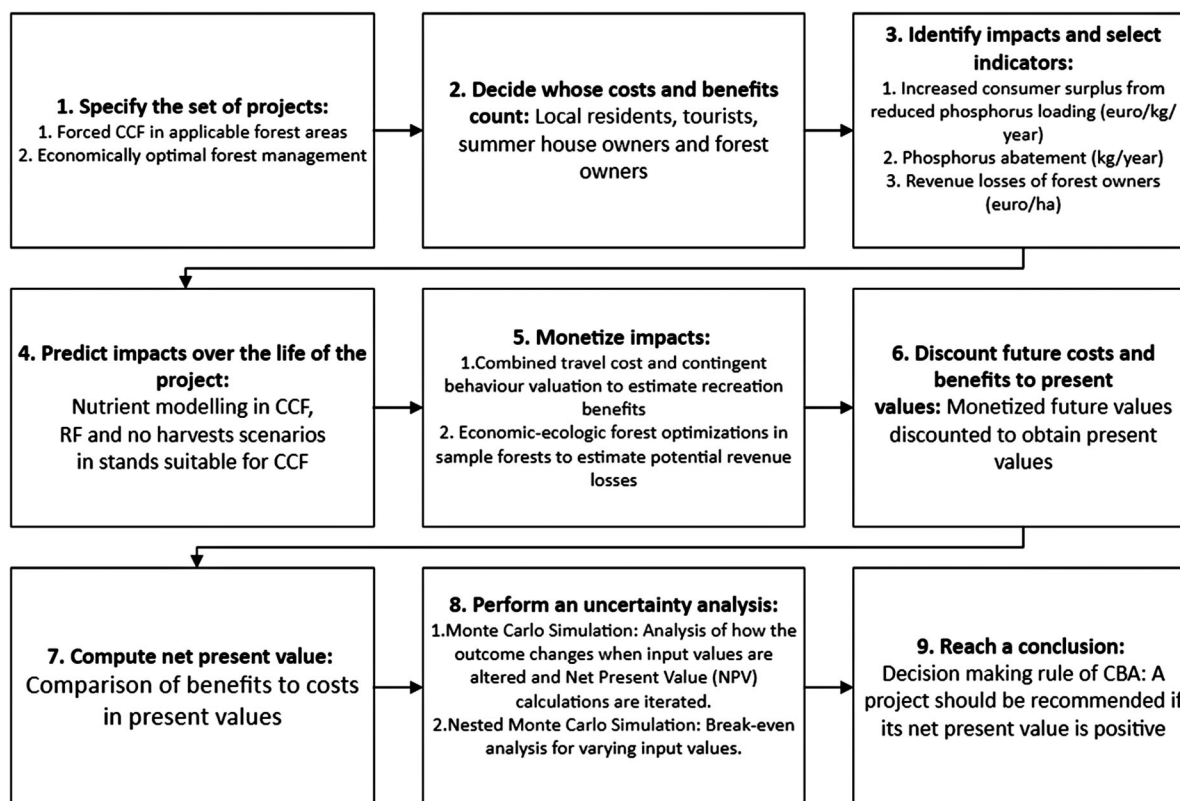


Figure 3. Structure of the CCF cost-benefit analysis following Boardman et al. (2017) and Pearce et al. (2006).

After nutrient modeling, benefit estimation, and cost calculation, a Monte Carlo (MC) analysis was used to calculate averages of the NPV distribution. This approach provides more robust estimates than a singular value and accounts for uncertainties, as suggested by Boardman et al. (2017). (For the detailed analysis, see equations 1–6 in the supplementary file.) The cost inputs include the aggregated area of herb-rich and mesic forest stands suitable for CCF and the uniform distribution of costs (euro/ha), with and without DNM, of CCF in these fertility classes. These cost estimates are based on producer prices without taxes and subsidies. This approach aligns with the study's resource management focus. The 1 ha unit cost estimates were treated as fixed in the uncertainty analysis, while the suitable area for cost aggregation was sampled. The benefit inputs included the annual reduction in P exports, the operational life of CCF, the number of vacation homes, the average household size in a vacation home, the proportion of inhabitants and vacation home household members participating in water recreation, and the total number of inhabitants.

Three separate simulations were conducted for different fixed discount rates (1%, 3%, and 5%) using the R programming language. A uniform distribution was selected for the inputs in the MC analysis due to the lack of empirical evidence that would justify any other specific distribution. The analysis was expanded into a Nested Monte Carlo Simulation (NMCS) by incorporating sensitivity analysis principles into the MC simulation by re-iterating the process and adjusting the fixed parameter of focus by a small increment for each batch of simulations. This procedure allows for the mapping of NPV distributions across a range of fixed parameters of focus. It also helps to estimate the threshold levels, i.e. the values at which the NPV becomes positive for a given parameter of focus.

Forest management scenarios and phosphorus export load

The effects of CCF on P export were examined by modeling forest management scenarios in current climate conditions (the 2006–2016 period) using the NutSpaFH_y model (Laurén et al. 2021) for a 10-year simulation period suitable for detecting clear-cut or thinning-induced nutrient export (Finér et al. 2010; Palviainen et al. 2015) in the Vehka-Kuonanjärvi sub-catchment. This open-source model, in terms of both code and data, allows application across boreal forested areas. We ran NutSpaFH_y using three different forest management scenarios: (1) “No harvests,” i.e. a reference “conservation” scenario, (2) “CCF” on currently suitable sites, and (3) “RF,” meaning clear-cuts on the same sites. The “No harvests” scenario includes recent clear-cuts or thinnings performed in the area before the simulation period, but no additional cuttings were simulated, and it provided the baseline P export load level, to which the exports under CCF or RF scenarios could be compared.

The NutSpaFH_y model requires gridded input data on forest resources (leaf and root biomasses, stand volume, stand age, tree height and basal area, site fertility) covering all the forest in the sub-catchment. These were derived

from the Finnish Forest Centre (FFC 2018) stand level data, which was rasterized in a 16 m × 16 m grid and complemented using multi-source National Forest Inventory (Mäkisara et al. 2016) data for areas missing in the FFC data. In addition, soil (GSF 2018), topography (NLSF 2019), and weather data (Aalto et al. 2016) within the sub-catchment boundaries (FEI 2014) were compiled for the study area. The model calculates the daily hydrology and monthly nutrient (N and P) balance in 16 m × 16 m grids and calculates the export from the forest area to the sub-catchment outlet in monthly time steps. In the model, the nutrient export from groundwater is delayed according to the water residence time. Nutrients are assumed to be utilized for various processes along their way to the outlet, which in the NutSpaFH_y model is considered by using logarithmic equations fitted to the data by Heikkinen et al. (2018).

A harvesting mask identifying the location of cuttings in the CCF and RF scenarios is required as input for the model. The stands with potential for CCF were identified as mature spruce-dominated peatlands with a herb-rich or mesic fertility class. In the NutSpaFH_y model, when either clear-cut or CCF-related thinning occurs, the grid-based information on the tree volume, height, leaf area, and tree age is updated. In the case of clear-cutting, the volume was updated to 5 m³/ha, the height to 2 m, the LAI to 0.1, and the age to 1 year, assuming immediate regeneration and the stand development following the same initial growth curve as described in Appendix B of Laurén et al. (2021). In the case of CCF, the original grid values for the stand volume, height, LAI, and age were multiplied by 0.4, assuming that 60% of the initial stand volume was harvested from the mature forests suitable for CCF. This assumes that the largest and oldest trees were removed from the grid under the CCF scenario. The nutrient balance was calculated considering these updated values. The nutrient uptake was reduced compared to the “No harvests” scenario, but it remained higher than in the RF scenario. Because of the reduced leaf area, as well as the decrease in interception evaporation and transpiration, the water table rises, which further reduces peat decomposition and nutrient release. For grids without clear-cuts in the harvest scenario, the nutrient export was modeled based on the initial forest data values and the expected growth (for details see Laurén et al. 2021). The clear-cut or CCF-related thinning was simulated to occur at the beginning of the simulation period, and the P export difference between RF and CCF was estimated by calculating the mean over the simulation period in kg/ha/year. A total annual P export value was calculated over the sub-catchment by aggregating the hectare-based values in P exports.

Recreation benefits

The recreation benefits of a water body can be influenced by water quality in two ways. Firstly, impaired water quality leads to a reduction in the number of recreational visits. Secondly, the overall welfare impact of a recreation visit is reduced with worse water quality. The benefit estimates are based on study by Tienhaara et al. (2021), where the annual recreational value of Lake Puruvesi was estimated under four water quality

Table 1. Recreational value of Lake Puruvesi under water quality classes corresponding to the ecological status of surface waters (Kristensen et al. 2018).

Recreational value of Lake Puruvesi/person/year, in 2020 EUR					
Water quality level in Puruvesi in Tienhaara et al. 2021	Corresponding Ecological status (Kristensen et al. 2018)	Total P loading kg/year (Tossavainen, 2019)	People cycling or walking to the recreation site, EUR /person/year	Other means of travel, EUR/person/year	Value/visit, weighted average of those walking or cycling and others, EUR/person/year (Tienhaara et al. 2021)
Excellent	High	203	93	4,218	3,702
Good	Good	368 ₂	84	3,003	2,638
Average			69	2,025	1,781
Poor	Moderate ₁	670	47	893	787

¹Water quality currently in the Savonlahti Bay according to Tossavainen (2019).

²Maximum allowed P concentration for good state in the Savonlahti Bay according to Tossavainen (2019).

levels: excellent, good, average, and poor, using the combined travel costs – contingent behavior method (TC-CB) (Table 1) which is a commonly used method to evaluate the economic value for the recreational use of nature under different environmental quality scenarios. In a TC-CB survey, data on the reported number of recreational visits to a certain area in the past and their associated travel costs, as well as a number of hypothetical visits in the future under different environmental quality scenarios are used to evaluate the monetary value of the visits under current environmental quality conditions and hypothetical future environmental quality scenarios. The evaluation of the monetary value of recreational visits is based on the idea that the costs of traveling to a recreational destination can be used as an approximation of the price of a recreation visit (Lankia et al. 2019; Bertram et al. 2020; Egan et al. 2022).

To integrate the valuation results from Tienhaara et al. (2021) with the P export modeling of this study, we connected the recreational value estimates associated with different water quality levels to the P exports in the Savonlahti Bay. This conversion process was structured in two phases. In the first phase, we mapped the water quality classes described by Tienhaara et al. (2021) to the ecological classification of water bodies as defined by the European Environment Agency (Kristensen et al. 2018, see Table 1). This mapping enabled us to align the recreational values with specific ecological statuses. In the second phase, we identified the P export levels in Savonlahti Bay corresponding to these ecological status classes, based on the work by Tossavainen (2019) (Table 1). This two-step approach allowed us to link the simulated P exports to the recreational value of different water quality levels as established by Tienhaara et al. (2021), ensuring a coherent framework for assessing the impact of P exports on recreational values in the Savonlahti Bay.

Consequently, we obtained recreational value estimates corresponding to different P export levels as a linear function between the annual recreational value per person and total annual P export values. When the ecological status is between moderate and good, a 1 kg reduction in the P export levels would yield a 6.55 euro increase in the recreational value of Savonlahti Bay per person per year, with a 95% confidence interval of 4.47–8.35 euros used as the range in the MC analysis.

The aggregated benefits of the reduced P export values in the MC analysis were calculated by multiplying the annual value of the recreational benefits per person per one kg

reduction in the P export level with the total reduction in P export level in kg from CCF and the total number of people visiting the Savonlahti Bay for recreation. The total number of visitors was estimated based on the number of inhabitants and summer cottages in the area. The number of summer cottages in the area was set between 150–321 and was calculated in ArcGIS software from building data from the National Land Survey of Finland Topographic Database (NLSF 2019) and sub-catchment boundaries by Finnish Environmental Institute (FEI 2014) and Savonlahti-bay area (Figure 1). It was assumed that on average two people use each summer cottage (Voutilainen et al. 2021). The range of summer cottage users was assumed to be between 1.9 and 2.2 based on previous average vacation household sizes (FCG Finnish Consulting Group 2016; Voutilainen et al. 2021).

The number of inhabitants in the area, 1,223–2,392, was calculated in ArcGIS from population data from Statistics Finland (OSF 2016). While all summer cottage users were assumed to visit the Savonlahti Bay for recreation, the same assumption was unrealistic for the inhabitants. Therefore, the range of inhabitants participating in water recreation in the MC analysis was estimated based on the proportion of inhabitants participating in water recreation in the Southern Savonia region, where the Savonlahti Bay is located (78%), and in the whole of Finland (81%). The range was obtained from the Finnish national outdoor recreation inventory data collected in 2019–2021 (Neuvonen et al. 2022). Multiplying the number of inhabitants in the area by the proportion of inhabitants participating in water recreation gives the number of inhabitants in the Savonlahti Bay area participating in water recreation, 1,875. The total number of people participating in water recreation in Savonlahti Bay, 2,517, was calculated by adding the number of summer cottage users to the number of inhabitants participating in water recreation.

Costs of continuous cover forestry

To obtain the costs of CCF, we calculate the decrease in the net present value of timber production over an infinite time horizon when, instead of an economically optimal solution, a solution that maximizes the net present value under immediate CCF is applied. This is done in two steps. First, we solve for the optimal solution starting from a bare land state. Second, we optimize the transition to this bare land state from an existing non-bare land initial state. If it is economically optimal to clearcut the stand at any point and then

follow the optimal solution from a bare land state, the immediate switch to CCF incurs costs. If it is optimal to never clearcut the initial forest, then an immediate switch to CCF incurs no costs and is economically optimal.

For this purpose, we build on the stand-level economic-ecological optimization model in Österberg et al. (2023). In the optimization model, we apply empirically estimated growth models for Norway spruce and Downy birch mixtures in peatland soils by Pukkala et al. (2021) in a size-structured transition matrix format. The stand growth model consists of species-specific and density-dependent functions for diameter growth, mortality, and natural regeneration. Following Finnish silvicultural recommendations, the optimization included an $8.0 \text{ m}^2 \text{ ha}^{-1}$ lower bound restriction on the stand basal area in outside bare land and seedling states that follow clearcutting (Vanhatalo et al. 2015). The DNM costs were included in the bare land value after a possible clearcut. As CCF can make DNM unnecessary but this is not guaranteed, we applied two different specifications for DNM costs. In the first specification, DNM costs occur in RF every 30 years starting from a bare land state, while in CCF, DNM is assumed to be needed only once in the bare land state. In the second specification, no DNM costs occur in either RF or CCF. In the cost-benefit analysis, the interpretation of the first specification is that by maintaining a continuous cover, CCF removes the need for DNM, while the interpretation of the second specification is that there is no difference in DNM requirements between RF and CCF. The economic-ecological optimization model includes species and size-class-specific sawlog and pulpwood volumes and species-specific sawlog and pulpwood prices. For a full description of the economic-ecological model, parameter values and optimization methods applied, see the Supplementary file.

The costs of an immediate switch to CCF were calculated separately for mesic and herb-rich stand fertility sample forests. The initial state of the stand structures for both fertility classes was constructed by first estimating the species-specific tree diameter (at breast height 1.3 m, DBH) distributions within $16 \text{ m} \times 16 \text{ m}$ grids, derived from the Finnish Forest Centre grid data (FFC 2018), in the Vehka-Kuonanjärvi sub-catchment, intersecting with the identified potential CCF stands.

These estimations utilized the multivariate mixed model equation developed by Siipilehto et al. (2007), which employs the Johnson's SB-distribution to predict diameter at breast height (DBH) distributions. This model integrates stand basal area, mean DBH, and stand stem number as inputs. Although initially constructed for Scots pine stands on drained boreal peatland sites, this model has demonstrated its capacity to reliably predict a diverse array of forest structures based on limited stand characteristics (Siipilehto 2011), and thus, we employed the model to predict the DBH distributions for Norway spruces and Downy birches in this study. Secondly, we computed the DBH distributions for each stand by aggregating data from all intersecting grids within the given stand compartment. Finally, we calculated an area-weighted mean DBH distribution for the two fertility classes, enabling an accurate representation of

diameter distributions at the stand level. For stands that did not intersect with the grid data, we utilized the FNN package (Fast Nearest Neighbor Search Algorithm) in R to assign the 10 nearest matching grids to these stands. These grids were selected based on their similarities in basal area, height, diameter, age, and volume. This approach was necessary for 9 out of the total 53 stands, which we were unable to match directly with the grid data. Finally, cost estimates were aggregated over suitable herb-rich and mesic stands in the MC analysis to calculate total costs. A separate analysis was conducted to include future potential herb-rich and mesic sites, with areas of 23.4 and 108.2 ha. These potential future CCF areas included stands maturing for clear-cutting in the next 30–50 years.

Results

Modeling outputs and inputs for sensitivity analysis

The modeling outputs, i.e. the input information used in the cost-benefit comparison, are summarized in Table 3. The differences in P export of CCF and RF scenarios compared to the No harvest scenario simulated with the NutSpaFHy model for the 2006–2016 period are shown in Figure 4. A yearly mean P export per hectare of areas suitable for CCF was calculated and used in further analysis. The results suggested that CCF reduced the P export levels compared to clear-cuts in RF, mostly due to a higher P uptake of the remaining trees and the role of vegetation for runoff. Generally, thinning or clear-cut influences the export levels for a 5–10-year period (Palviainen et al. 2015).

The P export reduction was 0.022 kg/ha/year , which sums up to 1.68 kg/year when aggregated over the suitable CCF forest area in the catchment area. In the "CCF" scenario, the P export level increased by 0.040 kg/ha/year compared to the "no harvests" scenario. In the "RF" scenario the P export level increased by 0.062 kg/ha/year compared to the "no harvests" scenario. Aggregating the annual recreational benefits of one kg reduction in P loading ($6.55 \text{ euro/person/year}$) over the population of the study area gives the estimate of the total annual benefits of one kg reduction in P loading, resulting in 16,480 euros.

The costs of applying CCF to existing forests (Table 2) were calculated separately for 1%, 3%, and 5% interest rates, for different stand fertilities and with and without DNM costs. Table 3 shows that an immediate switch to CCF has costs under a 1% interest rate, while under 3% and 5% interest rates there are costs only for herb-rich stands. Figure 5 shows the different stand volume developments for all optimal solutions and optimized CCF solutions. Low stand fertility, a high interest rate, and DNM costs favor CCF (Table 2, Figure 5). In all cases where the transfer to CCF had costs, it was optimal to clearcut the initial stand immediately. Additionally, in many cases where it was optimal to clearcut the initial stand immediately, it was favorable then to follow CCF from bare land (Figure 5h,i,l). Relative losses from an immediate transfer to CCF were 6–8% for mesic stands with a discount rate of 1%. For herb-rich stands, the relative NPV losses from optimal were between 18–19%

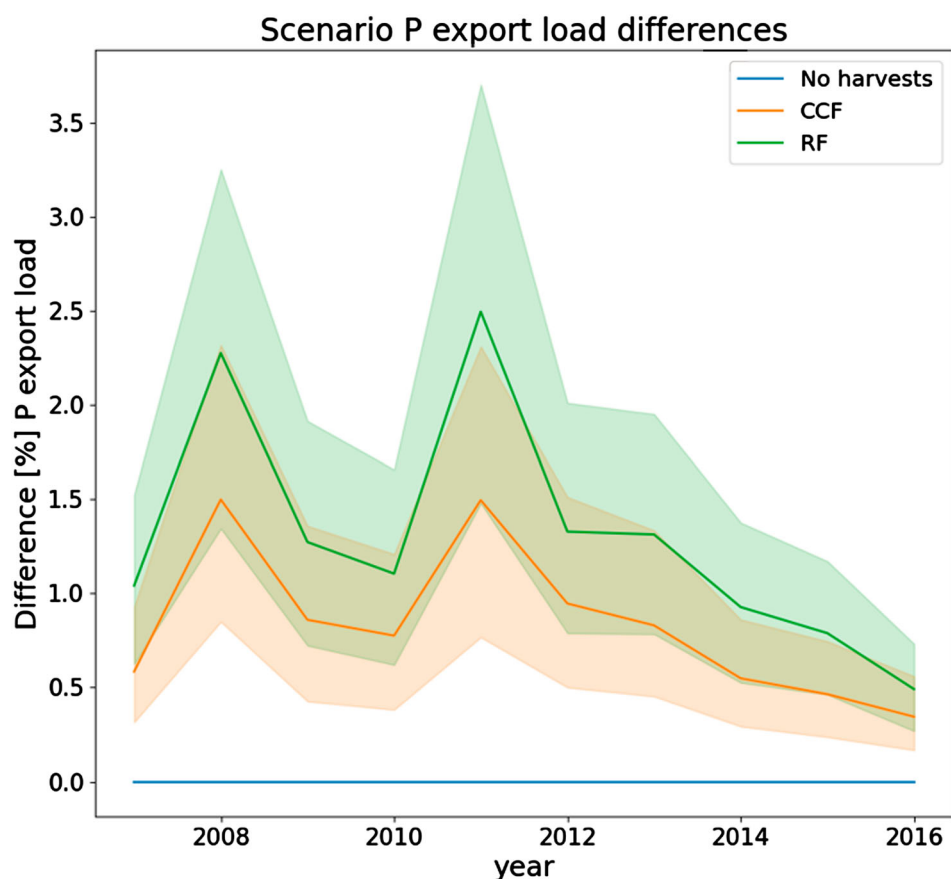


Figure 4. The difference in P export load between the “RF” and “CCF” scenarios compared to the “No harvests” scenario. The export varies due to differing runoff conditions and the varying intensity of cutting. The solid line represents the mean of the modeled export difference in the 33 sub-catchments (shaded area) of the Vehka-Kuonanjärvi area.

Table 2. P abatement, benefit and cost model outputs used in the cost-benefit analysis.

Output	Discount rate	Description	Value
P abatement		Yearly reduction of P loading, kg	1.68
Herb-rich sites costs	1%	Present value of revenue losses from immediate switch to CCF, euro / ha	11,411–12,499 ₂
	3%		1,503–1,831 ₂
	5%		379 – 659 ₂
Mesic sites costs	1%	Present value of revenue losses from immediate switch to CCF, euro / ha	2,801–3,889 ₂
	3%		0 ₁
	5%		0 ₁
Benefit from P reduction		Increase in consumer surplus from reducing 1 kg of P, €/person/year	6.55

¹Zero cost indicates that a transition to CCF through heavy thinning is the optimal management approach and thus continuous cover forestry is treated as cost free.

²Higher numbers omit the cost of DNM.

with a discount rate of 1%, 6–7% with a discount rate of 3%, and 2–4% with a discount rate of 5%. The characteristics of the optimized CCF solutions can be found in the supplementary material (Supplementary Table 6).

Sensitivity analysis and cost-benefit comparison

The results from the CBA (Table 3) show that the benefits of CCF outweigh its costs in its primary role of preserving water quality, as evidenced by a positive NPV in all scenarios.

Table 3. Monte Carlo simulation outcomes: average net present value (NPV), average present value of benefits and average present value of costs in million euros with standard deviation in brackets.

Discount rate	Average NPV	Average present value of benefits	Average present value of costs*	95% CI for NPV	Average benefit-cost ratio
1%	1.61 (0.46) / 1.47 (0.47)	1.96 (0.46) / 1.96 (0.46)	0.35 (0.02) / 0.49 (0.07)	0.92–2.43 / 0.76 – 2.30	5.68 / 4.05
3%	0.64 (0.15) / 0.62 (0.15)	0.65 / (0.15) / 0.65 (0.15)	0.018 (0.001) / 0.03 (0.006)	0.40–0.91 / 0.39 – 0.90	37.08 / 24.33
5%	0.39 (0.09) / 0.38 (0.09)	0.39 (0.09) / 0.39 (0.09)	0.006 (0.001) / 0.008 (0.002)	0.25–0.55 / 0.24 – 0.55	73.11 / 47.89

95% confidence interval (CI) for NPV, and average benefit-cost ratio for 100,000 simulations. NPV estimates with potential future areas are shown after the /–sign.

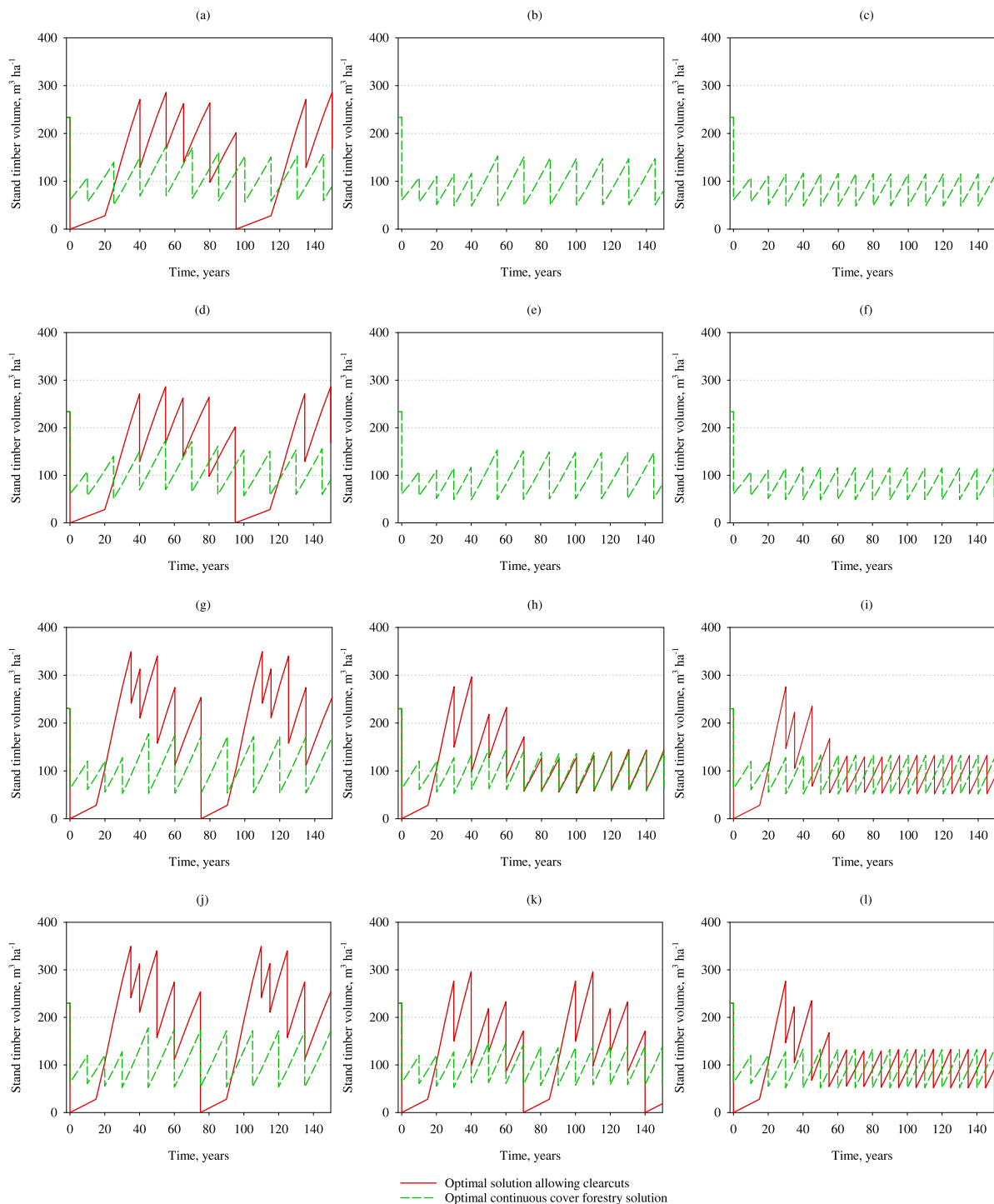


Figure 5. Stand volume developments for optimal solutions allowing clearcuts and for optimal immediate continuous cover forestry solutions. Mesic (a)–(f) and herb-rich (g)–(l) stands. DNM costs are included in (a)–(c) and (g)–(i) and omitted in (d)–(f) and (j)–(l). The interest rate is 1% in (a), (d), (g), and (j), 3% in (b), (e), (h), and (k), and 5% in (c), (f), (i), and (l).

Note: Only the first 150 years shown. The stand timber volume is the sum of Norway spruce and Downy birch volumes (see Supplementary file for details). DNM = ditch network maintenance. DNM costs do not change mesic solutions. In (b), (c), (e), and (f) the optimal solution is immediate switch to continuous cover forestry.

Notably, a higher discount rate makes CCF an even more attractive solution by reducing potential revenue losses.

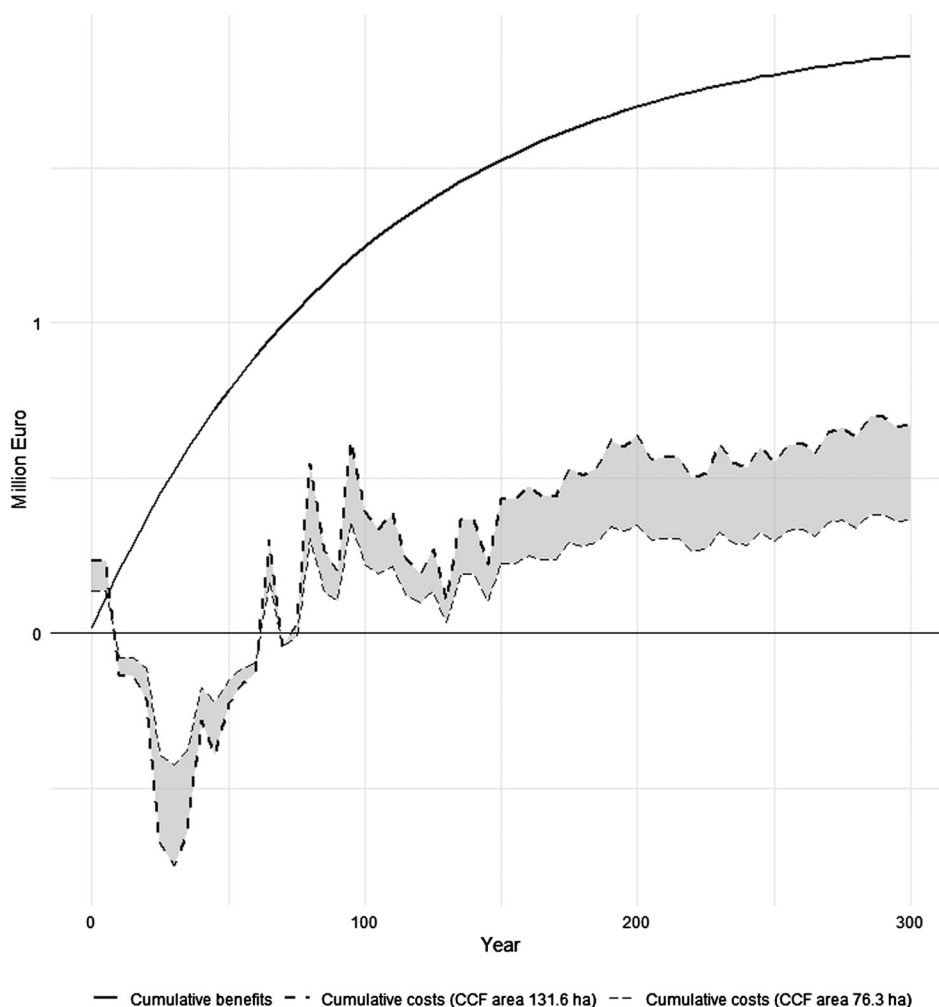
Threshold values that turned the MC simulation NPVs positive (Table 4) were calculated using the NMCS-framework. Significant changes in the cost and benefit estimates would be required, while keeping other factors constant to turn the expected NPV negative. This is especially noteworthy in

the context of abatement, as the nutrient modeling and optimization are not directly linked (Figure 2): A 74.88% percent reduction in the abatement estimates would be needed to make the NPV negative in the most conservative scenario.

Figure 6 depicts the time dynamics of the analysis with a discount rate of 1% over the first 300 years. The continuous

Table 4. Nested Monte Carlo simulation, including potential future CCF areas, break-even threshold values across different discount rates (100 nested iterations for each increment of the parameter of interest).

Parameter	Threshold value, 1% discount rate	Threshold value, 3% discount rate	Threshold value, 5% discount rate	Description / unit
Abatement	0.422	0.074	0.038	Yearly reduction of phosphorus loading, kg/year
Consumer surplus from recreation	1.64	0.28	0.14	Consumer surplus, euro/year/person, from water recreation
Costs of continuous cover forestry	12,131	6,396	3,936	Forest owners' loss of revenue, present value, €/ha
Population participating in water recreation	776	132	68	Number of individuals participating in recreation activities in the study area.

**Figure 6.** Time dynamics of cumulative costs and benefits in CCF scenarios with a 1% discount rate without DNM costs.

Note: 76.3 ha (86.1% mesic, 13.9% herb-rich), 131.6 ha (83.2% mesic, 17.8% herb-rich, see Table 3). Note: Only the first 300 years shown.

line illustrates the cumulative benefits under a 1% discount rate scenario. The dark grey area between the dashed lines represents the cumulative revenue losses with a 1% discount rate without DNM costs, i.e. the most conservative scenario, aggregated over the suitable forests at the study site (Table 2). The dashed line marks the lower bound of the area applicable for CCF within the study site, while the bolded dashed line indicates the upper bound (as detailed in Table 2). Initially, the costs, which are due to cutting restrictions that a “forced” CCF imposes, are larger than the accumulating benefits for forest owners whose forests are ready for clear-cutting. However, the benefits begin to outpace revenue

losses shortly thereafter. After 15 years, CCF becomes more economically advantageous than the optimal solution – that is, it incurs lower costs – until around year 60, at which point the unrestricted optimal solution begins to yield greater returns than the immediate implementation of CCF.

Discussion

The results of the CBA indicate that CCF is socially a potential solution for mitigating the adverse effects of nutrient exports in the study area. However, this measure alone is insufficient to significantly alter the trajectory of water quality

development. The NutSpaFH_y modeling results suggest that CCF enables an average reduction of 1.68 kg/year, which represents 7–11% of the total reduction target and 19% from the Lake Kuonanjärvi target (Tossavainen, 2019; see also Figure 1). This is a sizable proportion considering that mature peatland spruce forests (76.3 ha) cover only roughly 1.5% of the total forest area (5,190 ha) in the studied sub-catchment area. These mature stands are the next to be harvested and are likely to contribute to an increase in exports, if clear-cut. The benefit potential is likely higher, considering that 9% of the sub-catchment is covered by spruce-dominated peatland forests with a fertility class suitable for CCF, which has a reduction potential of 44–66% from the total reduction target for forestry (Tossavainen, 2019) if all development classes, not just mature stands, are converted to CCF.

Studies like Österberg et al. (2023) demonstrate that in many cases, CCF is economically optimal from bare land. In addition, Malo et al. (2021) show that the larger the number of large trees in a non-bare land initial stand, the greater the economic incentives to clearcut the initial stand. Given that the initial states in this current study represent mature spruce-dominated stands, the conversion of younger stands than considered here would likely be achieved with lower to no costs. Our results suggest that switching to CCF immediately after heavy thinning is the optimal forest management strategy for the sample forests when the discount rate is high and/or the stand is less nutrient-rich, implying no cost to forest owners. If forest owners predominantly use RF, adopting CCF would increase revenues and further improve CCF's NPV. Furthermore, the NPV estimates are likely underestimated, as they did not quantitatively consider carbon sequestration impacts. Recent studies have demonstrated the potential of CCF for peatland carbon sequestration (Shanin et al. 2016; Nieminen et al. 2018; Korkiakoski 2020; Shanin et al. 2021; Lehtonen et al. 2023). Costs were calculated with and without DNM, where the inclusion of DNM gives the lower bound of the costs, while leaving DNM costs out, i.e. assuming that they are identical, gives the upper bound estimates for DNM. The actual cost is most likely somewhere in between, as CCF can reduce the need for DNM (Nieminen et al. 2018; Leppä et al. 2020), but not completely.

Under 3% and 5% interest rates, the overall total costs (Table 3) were lower than those in a previous CCF study (Juvonen 2020) which used a similar optimization framework but a single fertility class and different growth models (Pukkala et al. 2013). The costs of an immediate CCF transition are modest because the forests in our model are not entirely excluded from forestry activities as in the case of “no harvests” scenario. If they were, the costs to forest owners would be optimized for the NPV of timber production revenues, which would be significantly higher. This approach was employed in a previous study (Juvonen 2020) where the costs of riparian buffer zones were estimated under the assumption that all forests within 15 meters of water bodies would be excluded from harvesting, resulting in an NPV loss of approximately 865,000 euros in the same study area.

While our CBA indicates potential for CCF, cautious interpretation is necessary due to several factors. The

quantified impacts of CCF, particularly regarding natural regeneration, are understudied and primarily based on modeling. The complexities of modeling the P dynamics (Janes-Bassett et al. 2020) require careful interpretation due to spatial data constraints. The economically optimal choice between CCF and RF depends on various economic and ecological factors and modeling approaches (Tahvonen 2022; Tahvonen et al. 2022; Österberg et al. 2023). Current stand growth models suitable for optimizing both RF and CCF do not account for factors such as ditch network maintenance, which could affect the costs of transitioning to CCF. The optimization of the sample forest was computationally demanding, which is why it was not possible to include it in the MC simulations. Further, for this reason cost aggregation was used in the first place instead of running an optimization algorithm separately for each stand for each discount factor and DNM cost scenario. In addition, forest regeneration and growth are still highly uncertain in the growth and yield models.

Assessing CCF's non-market benefits, particularly linking reduced nutrient loading to water quality and recreational experiences, is complex. While initial studies provide insights, the specific effects of P reduction on the improvement of water quality are not fully understood. Direct, primary valuation studies would likely yield more precise estimates for benefit components. Moreover, benefits and CBA results are highly sensitive to input parameters, particularly when evaluating the recreation values of inland waters, which vary greatly based on the lake characteristics. This heterogeneity, influenced by distinct spatial and biological features, underscores the challenge of applying uniform benefit assessments across different areas. A threshold value analysis can provide guidelines for determining recreation value requirements before undertaking a comprehensive analysis.

Though spatially specific, our results suggest that shifting to CCF could benefit boreal peatland forests (249.5 million hectares, Leifeld and Menichetti 2018) by enhancing water protection, recreation, and carbon sequestration. The costs, primarily revenue losses, could be offset by governments if the NPV is positive. At the sub-catchment level, the macroeconomic effects of a wide CCF transition are likely to be minimal, but on regional, national, or global scales, the management shift towards CCF could impact supply, demand, and wood product prices, thus influencing optimal management through the prices of different wood products.

Forest growth is described using empirically estimated models by Pukkala et al. (2021) under the current climate. Climate change, with increasing annual temperature sums could favor RF by boosting growth, thereby increasing CCF costs. Conversely, higher temperatures might enhance natural tree regeneration, favoring CCF and reducing costs. Climate change introduces an accumulation of uncertainties in evaluating the background nutrient export levels without the impact of management and management-induced nutrient exports since temperature and precipitation are key drivers for the nutrient balance, and forest operations both temporally and spatially influence the resulting nutrient export levels. Despite this, as also found by Leinonen et al. (2023), identifying cost-effective measures to reduce nutrient

loading in current and future climate conditions is important. Climate change impacts on recreational values are influenced by the water quality trajectory of substitute sites. If a nearby lake deteriorates more rapidly than the CCF treated site under climate change, it could lead to a substitute effect where visitors from the degraded site prefer the study site, thereby increasing its recreational value and the NPV of CCF. Further research is required to fully understand these dynamics.

Our findings indicate that CCF, particularly for mesic stands, has potential benefits for forest managers by offering a viable alternative to RF with lower environmental impacts. From a policy perspective, this research provides insights into monetizing both the positive and negative externalities of forestry, as well as the diverse ecosystem services forests offer at a localized level. Results suggest that direct market interventions, such as subsidies or taxes, may be unnecessary. Instead, enhancing awareness among forest owners about the private and social advantages of CCF could represent a more resilient approach amidst the uncertainties surrounding broader market-level impacts. By equipping forest owners with the knowledge and tools for sustainable management, CCF practices can better align with both personal and societal environmental and economic objectives.

Further research is required to refine best practices for CCF and to develop models that accurately quantify its long-term effects, accounting for uncertainties, including those posed by climate change. Accurate quantification of the externalities associated with CCF is essential to developing effective strategies and mechanisms that support global and national objectives, such as carbon sequestration, water conservation, and biodiversity preservation. A rigorous data-driven approach can better inform policymakers in designing strategies that ensure forestry practices are in harmony with broader environmental and sustainability goals.

Conclusions

In this study, we assessed the cost-effectiveness of CCF management in mature peatland spruce-dominated forests to mitigate nutrient loading into Lake Puruvesi, using the framework of CBA. Modeling was employed to evaluate the nutrient loading conditions from RF and the potential impacts of CCF. Phosphorus abatement was estimated to be around 1.68 kg annually for a mesic and herb-rich forest area of 76.3 ha converted to CCF. Costs were estimated using a size-structured forest optimization model in mesic and herb-rich stands, while recreational benefits from phosphorus abatement were evaluated with a combined travel cost-contingent behavior model. The nutrient modeling results indicate that CCF alone may not effectively meet reduction targets at the study site, achieving a reduction of only 7–11% of phosphorus from the total reduction target. However, the economic comparison of welfare impacts from this reduction yielded positive net present values across all scenarios. The most conservative scenario yielded a benefit-cost ratio of 4.05, highlighting

CCF's potential for uptake in boreal peatlands with high recreational value.

Author contributions

Jaakko Juvonen (JJ), Tuija Lankia (TL), Aura Salmivaara (AS), Vesa-Pekka Parkatti (VP), Eija Pouta (EP), Heini Ahtiainen (HA), Eeva Kuntsi-Reunanen (ER), Annika Tienhaara (AT), Annamari Laurén (AL), Marjo Palviainen (MP), Sakari Sarkkola (SS), Liisa Ukonmaanaho (LU).

Conceptualization JJ; Methodology: JJ; AS; AL; VP; TL Visualization: JJ; AS; VP; Supervision: JJ; Formal analysis: JJ; TL; HA; AT; AS; VP; SS; Writing – Original Draft: JJ; TL; EP; AS; VP; Writing – Review & Editing: JJ; TL; ER; EP; AS; VP; MP; AL; SS; Project administration: LU.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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