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Continuous Cover Forestry and Cost of Carbon Abatement on Mineral Soils and Peatlands

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Continuous cover forestry (CCF) has proven to financially outperform rotation forestry (RF) with low or even moderate social price of carbon in mineral soils. However, to date there are no studies to compare financial performance of joint production (timber and carbon sequestration) between mineral soils and peatlands when CCF is applied. A vast variety of harvest intervals and intensity (expressed as post-harvest basal area) for a mature spruce-dominated [*Picea abies* (L.) Karst.] stand on both mineral and peat soils was simulated with process-based ecosystem model, EFIMOD. In addition, four levels of carbon price (0, 25, 50 and 75€/tCO_2) were applied in assessing the profitability of joint production (timber and carbon sequestration) associated with CCF. Mineral soil turned out to be superior to peatland in cost-efficiency of carbon sequestration. For instance, the cost of additional ton of CO_2 was only €2/tCO_2 with a carbon price of €25/tCO_2 for a private forest owner (through carbon trading), while on peatland it fluctuated between €30 and €39.5/tCO_2, depending on the carbon price applied for a private forest owner (€25-€75/tCO_2). In general, mineral soil was more sensitive to harvest interval and intensity than peatland, with respect to cost-efficiency in climate change mitigation.

Keywords: continuous cover forestry, cost of carbon abatement, mineral soil, peatland, net present value, rotation forestry

INTRODUCTION

Climate change is basically driven by an imbalance in the global energy budget (Lintunen et al., 2021). The imbalance is mainly due to carbon dioxide (CO_2) emissions increased by human activity, i.e., anthropogenic emissions (e.g., Stern et al., 2006; IPCC, 2021). In brief, anthropogenic emissions cause radiative forcing which further creates global warming corresponding to the gradual increase in global surface temperature (IPCC, 2014). It is a well-demonstrated fact that these anthropogenic emissions of greenhouse gases (GHG) have damaging impacts on earth's atmosphere (e.g., IPCC 2014; Gren and Aklilu, 2016). Thus, recognition of the need to stabilize (or even decrease) the C content in the atmosphere has been manifested in various international and national agreements and policies—such as the Kyoto Protocol (e.g., Lutz and Meyer, 2009), the Paris Climate Agreement (e.g., Juutinen et al., 2018a), and the EU climate action and the European Green Deal (e.g., Bieroza et al., 2021).

Reaching climate mitigation objectives requires immediate action (Masson-Delmotte et al., 2018), and the forest sector (incl. forests) is seen as an important contributor (Eriksson, 2015; Riahi et al., 2017; Jhariya et al., 2019; Raj and Jhariya 2021; Riviere and Caurla, 2021). Forest ecosystems account

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for app. 80% of aboveground terrestrial C and 70% of soil organic C (Dixon et al., 1994; Hui et al., 2017), presenting a positive net C balance (Lal, 2005), i.e., a net C sink (Pan et al., 2011). Boreal forests play a key role in C uptake because they are estimated to contain the highest C stocks per area unit after wetlands (IPCC, 2001), and the soil C stock in boreal forests represents a distinctively dominant proportion of total C stored (Mayer et al., 2020). In practice, the accumulated C can be stored in the forest to increase the C stock and/or harvested for consumption and further to substitute for fossil origin products reducing fossil C in the atmosphere (Lundmark et al., 2018). As a rule of thumb, less intensive thinnings maintaining higher growing stock volumes and applying longer rotation periods both increase C stocks in forests (Liski et al., 2001; Pukkala et al., 2011; Zubizarreta-Gerendiain et al., 2016). Recently, continuous cover forestry (CCF) has been demonstrated to enhance C storage in boreal forests (Assmuth and Tahvonen, 2018; Kellomäki et al., 2019; Shanin et al., 2021). Contrary to rotation forestry (RF), CCF applies partial selection cuttings (i.e., thinnings) without clearcutting and relies on continuous natural regeneration (Kuuluvainen et al., 2012).

Regarding possible differences between forests on mineral soils and peatland forests, C stock in the peat layer of boreal forested peatlands can be up to ten times larger compared to mineral soil forests (Weishampel et al., 2009). The difference is due to the naturally high ground water level (WL) of peatlands which slows down the decomposition of organic matter and favours accumulation of partly decomposed material as peat (Ojanen et al., 2010). Drainage for forestry lowers the WL exposing deeper peat layers to decomposition, which, in turn, create CO_2 emissions from soil with a magnitude that might turn the drained sites into net sources of CO_2 to the atmosphere—unlike the pristine (unmanaged) peatlands and mineral soils (Nieminen et al., 2018; Shanin et al., 2021). In drained peatlands the depth of the WL is affected by microclimate and the forest stand's evapotranspiration capacity (Leppä et al., 2020a) and also by forest management (e.g., ditch network maintenance, DNM (Lauren et al., 2021). In brief, in drained peatlands WL affects the whole ecosystem C balance in the long term, and all ditching operations likely result in enhanced peat decomposition in deeper layers with corresponding increase of GHG fluxes (Ojanen and Minkkinen, 2019). Significant net C emissions may release from the most productive nutrient-rich site types (Ojanen et al., 2013). The WL can also be maintained at a desired level by utilizing the evapotranspiration of trees through controlling the stand density (Leppä et al., 2020b). For both site categories (mineral soils and peatlands) CCF may enable more efficient C sequestration due to the absence of treeless stage—compared to traditional RF with clearcutting and DNM (Shanin et al., 2021). Further, avoiding DNM by applying CCF on peatlands decrease or may even dispose all the detrimental impacts resulting from RF on several ecosystem services by peatlands (Nieminen et al., 2018).

The social cost of C (SCC) is a measure to monetize the damage from releasing a ton of CO_2, and pricing C according to SCC provides the correct economic incentive for reducing current emissions (van den Bijgaard et al., 2016). Further, a price on C might help shift the burden for the damage from GHG emissions back to those who are responsible for it and who can avoid it (The World Bank, 2020). Despite criticism in general on C pricing[1], scholars and academia share a common view that some measure (price) is needed in order to provide an incentive for households, firms and governments to reduce emission cost-effectively. Principally and in the long run, the prospect of continuing and possibly rising C prices also provide a motivation for innovations to lower the cost of reducing emissions (Boyce, 2018).

In environmental policy, C services can be administered in different ways (Pohjola and Valsta, 2007; Verkerk et al., 2020). For instance, governments may use tax and subsidy-based instruments in forest ecosystems to incentivise meeting emission targets (Pohjola and Valsta, 2007; Evison, 2017; Juutinen et al., 2018b). In short, the amount of C sequestration within a forest stand depends on the level of growing stock, which in turn is controlled by thinnings and harvest(s) (Pohjola and Valsta, 2007; Pyörälä et al., 2014). This applies for CCF as well as for RF (Assmuth and Tahvonen, 2018). Then the rate of soil C sequestration is driven by litter input of growing stock, natural mortality and amount of harvest residues (Jhariya 2017a; Jhariya 2017b). Introducing C sequestration objectives affects optimal forest management in various ways by imposing changes to business-as-usual management and/or optimal management regimes (van Kooten et al., 1995; Olschewski and Benitez, 2010; Matthies and Valsta, 2016; Zengin and Unal, 2019). Basically, it is a question whether these changes are financially viable for a landowner to apply, and at the same time whether they generate a net amount of sequestered C in excess of *status quo*, a predetermined baseline C stock - thus creating an additionality (Asante and Armstrong, 2016).

Recent studies on CCF have focused on comparing the financial performance of CCF and RF on mineral soils with either one dominant tree species (e.g., Tahvonen, 2016; Tahvonen and Rämö, 2016; Parkatti et al., 2019) or mixed-species (Tahvonen et al., 2019; Parkatti and Tahvonen, 2020), but there is a lack of papers tackling with CCF on peatlands (Juutinen et al., 2021). Further, to our knowledge there are no articles assessing joint production of timber and carbon sequestration on peatlands except Shanin et al. (2021) that analyses the effect of CCF on the CO_2 and methane (CH_4) emissions from nutrient-rich drained peatland sites in southern Finland. This study is the first attempt to compare financial performance of joint production (timber and carbon sequestration) between mineral soils and peatlands when CCF is applied as a management regime. Then, special emphasis is laid on alternative C prices to discover trade-offs between timber production and C sequestration, and to find out whether it would

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[1] For a concise literature on C pricing shortfalls, see Stoll and Mehling (2021). Regarding unsolved issues related to SCC, see Belfiori's (2017) demonstration on the discrepancy between optimal C tax and SCC, Nordhaus and Boyer (2003), Weitzman (2007), and Stern (2008) for the applied discount rate in assessing and Ricke et al. (2018) for heterogenous geography of climate damage and global SCC.

be cheaper (more cost-efficient) to mitigate emissions in forests on mineral soils or on peatlands. Our hypotheses are: 1) Mineral soil and peatland differ from each other with respect to how cost-efficient the C sequestration through CCF would be, 2) peatland soil is a C source and therefore C pricing on peatland has negative effect on private forest owners' incomes, and 3) C pricing leads to less intensive harvests in CCF compared to absence of C pricing.

MATERIALS AND METHODS

Input Data

Analyses were based on a virtual forest plot obtained by aggregating the empirical plot-wise tree stand data from two experimental sites in the southern boreal zone of Finland (for further details, see Juutinen et al., 2021; Shanin et al., 2021). These sites were dominated by mature Norway spruce forests with admixture of downy birch (*Betula pubescens* Ehrh.). The initial stand characteristics were identical for mineral soil and peatland case in terms of size-class distribution and number of trees. The generated simulation plot represented a mixed uneven-aged stand with 1,212 trees ha^{-1} and basal area (BA) of 24.6 m^2 ha^{-1}. The diameter at breast height (DBH) of trees varied between ca. 0.3–38.5 cm (mean 13.5 cm), and the tree height fluctuated between 1.3 and 27.2 m (mean 12.9 m). The resulting distribution of trees among DBH classes was bimodal, peaked at middle (15–20 cm) and smaller (<5 cm) size classes. Then, 89% was spruce and 11% was birch, and the size-class distribution was similar for both tree species (Juutinen et al., 2021; Shanin et al., 2021). The initial soil C for the mineral soil site was set to 8.16 kg m^{-2} (1.34 kg m^{-2} in forest floor, and 6.82 kg m^{-2} in mineral horizons), and the initial C stock in the peat layer of peatland site was set to 147.36 kg m^{-2} (the thickness of peat layer is 2 m).

EFIMOD Model and Stand Projections

For producing stand projections in the generated simulation plot the EFIMOD model (Komarov et al., 2003) was applied. The EFIMOD is a spatially explicit, individual-tree based model that simulates the biological turnover in tree-soil systems. EFIMOD operates with an annual time step. A simulated stand consists of individual trees which interact with neighbouring trees. Each tree forms a shadow zone and nutrition zone, the sizes of which depend on the tree size. The shape of the rooting zone and crown of an individual tree is defined by the availability of resource (nitrogen in the soil and light) and interaction of an individual tree with neighbouring trees (Shanin et al., 2015; Shanin et al., 2020). The biomass increment of each tree is calculated on the basis of consumed soil nitrogen and intercepted solar radiation. This biomass increment is allocated between above- (stem, branches and foliage) and below- (coarse and fine roots) ground compartments, and the corresponding litter inputs are calculated based on the annual mortality rate of each compartment. Total litter production at the stand level also included the litter input from dead trees, as well as felling residues. Then, the three main components of C balance (C sequestration to living biomass and to dead organic matter), litter production and C losses due to decomposition of litter and peat layer) were included in the EFIMOD simulations (for further details, see Shanin et al., 2021). Briefly, on mineral soil the rates of decomposition of soil organic matter (both humification and mineralization) were simulated with process-based model Romul_Hum (Komarov et al., 2017), according to which they are dependent on temperature and moisture of the forest floor and the mineral soil, as well as on the nitrogen and ash content in the litter. The main outputs of the Romul_Hum model are C stocks in forest floor, labile and stable humus of mineral soil horizons, and CO_2 emission from decomposition. The model does not explicitly consider the soil horizons, but the simulated pools can be considered as organic layer and topsoil. However, this model has some limitations for application on peatlands, and therefore for this site only the decomposition of fresh litter was simulated with the Romul_Hum model, while the net CO_2 and CH_4 emissions from decomposing peat layer was calculated with the empirical equations, which quantify the relationship between emissions and soil water table (Shanin et al., 2021 for more details). However, the export of dissolved organic C was excluded from the analysis, because it may be transferred from organic layer but will accumulate on topmost mineral soil layer just below organic layer (Lindroos et al., 2008), and therefore this process has minor importance. With regard to a specific feature on peatland forestry, namely the ground WL the stand dynamics were linked to the WL level by specific models (Juutinen et al., 2021). Further, the influence of the WL on the net primary production and stand regeneration was also modelled with the EFIMOD system (Shanin et al., 2021).

The simulation scenarios of CCF (produced by EFIMOD simulations) were identical to those applied in Juutinen et al. (2021) and Shanin et al. (2021) and consisted of a series of selection cuttings initiated at the first step of simulation, where trees were removed, following the principles of CCF, mainly from the dominant and intermediate tree layers. The period between two consecutive selection cuttings was defined by the harvest interval R, which was set at 10, 15, 20, and 30 years, and the harvest intensity was defined by the post-harvest stand BA with values of 4, 6, 8, 10, 12, 14, and 16 m^2 ha^{-1}. Each cutting action assumed harvest of the larger trees but with retention of 5% of largest ones as seed trees. Harvesting was simulated as roundwood outturn of trees selected for cutting, while the harvesting residues, i.e., branches and foliage, stumps and belowground parts were assumed to be left on site. The length of the simulation period was set at 240 years. For peatland case management each scenario was simulated as two variants: with and without ditch network maintenance (DNM) since the gradual deterioration of the ditches overgrown by vegetation in time can result in rising WL levels. Further, in the variant with DNM, the DNM was carried out every 60 years in the cases of post-harvest BA of 4 and 6 m^2 ha^{-1} and every 120 years in the case of post-harvest BA of 8 m^2 ha^{-1} to maintain the WL below 0.35 m, at which levels it is assumed not to have significant effects on the growth and regeneration of trees (Juutinen et al., 2021). At the BAs higher than 8 m^2 ha^{-1}, due to high evapotranspiration capacity of growing trees, WL remained below 0.35 m without DNM (Sarkkola et al., 2009; Juutinen et al., 2021).

Financial Performance

Recall we simulated 28 different CCF scenarios with varying harvest intervals and post-harvest BAs. The profitability of each scenario was determined by calculating the net present value (NPV) of harvest revenues. Denote the harvest interval (years) in scenario s by $\hat{t}_s$ ($\hat{t}_s = 10, 15, 20 \text{ and } 30$) and the duration of the simulation period (years) by T (T = 240). After T years the stand and harvests were assumed to be in a steady state. Let volumes of harvests (m^3 ha^{-1}) at time t for scenario s be denoted by h_{lts}, and h_{pts} and the roadside prices by p_l and p_p for sawlogs and pulp, respectively. With this notation, the harvest revenues become $R_{ts} = h_{lts}p_l + h_{pts}p_p$. Considering costs, denote to the variable harvest costs (€ ha^{-1}) at period t in scenario s by C_{ts} including cutting and haulage costs: $C_{ts} = c_{ts}(h_{lts} + h_{pts} + h_{wts})$, where c_{ts} refers to unit harvest costs (€ m^{-3}) and h_{wts} to waste wood volume. Let $\hat{C}_t$ refer to the fixed harvest costs (€ ha^{-1}) at period t. Denote the cost of DNM at period t by $\hat{C}_{DNMt}$ and the time interval in which DNM is conducted in scenario s by $\hat{t}_{DNMs}$. Regarding the C sequestration, we postulate a subsidy/tax mechanism in which landowners receive a subsidy for C uptake, and pay a tax when C is released due to harvesting. Denoting the change in C stocks for stand and soil respectively with q_t and q_s and the C price with p_c, we can denote the C subsidy/tax in scenario s at time t with $Q_{ts} = p_c{*}(q_t + q_s)$. With these, using e^{-rt} as the discount factor (r is the interest rate), we can calculate the NPV (π_s) of scenario s with

$$\begin{aligned}\pi_s = \sum_{t=0}^{T}\Big(R_{ts} - C_{ts} - \hat{C}_t - \hat{C}_{DNMt} + Q_{ts}\Big)e^{-rt} + e^{-rT}\Bigg[\Bigg(\Big(R_{Ts} - C_{Ts}\\ - \hat{C}_l\Big)e^{-r\hat{t}_s} + \sum_{t=T-\hat{t}_s}^{T} Q_{ts}e^{-r\left(t-T+\hat{t}_s\right)}\Bigg)\Big(1 - e^{-r\hat{t}_s}\Big)^{-1}\\ - C_{DNMT}e^{-r\hat{t}_{DNMs}}\Big(1 - e^{-r\hat{t}_{DNMs}}\Big)^{-1}\Bigg] \qquad (1)\end{aligned}$$

The roadside prices, unit costs, and the time consumption models used to calculate the variable unit harvest costs were the same as in Juutinen et al. (2021). Variable unit harvesting costs were €95 h^{-1} and €80 h^{-1} for cutting and haulage, respectively, and time consumption both for CCF and RT were based on Väätäinen et al. (2010). For planting costs, the cost of site preparation was €382.8 ha^{-1}, €633.2 ha^{-1} for planting (including labor and material costs), €374.8 ha^{-1} for tending, and €429.6 ha^{-1}for pre-commercial thinning. Costs for DNM was €201.6 ha^{-1} based on Juutinen et al. (2021) where ditches were assumed to be parallel, with 50 m between their mid-lines, and using deflated (according to cost-of-living index) average unit prices of years 2013–2017. Finally, roadside prices for sawlog (pulp) for spruce were €57.73 m^{-3} (€30.40 m^{-3}) and for birch €47.39 m^{-3} (€29.58 m^{-3}). Climate subsidies are based on EU ETS prices. 25 €/t CO$_2$eq. is close to long-term average, 50 €/t CO$_2$eq is close to pricing in spring 2021, and 75 €/t CO$_2$eq. a potential future pricing.

RESULTS

Mineral Soils

On mineral soils, in baseline with 3% interest rate and no C subsidies, the best scenario with the highest NPV is the most intensive option with 10-year interval and 4 m^2 ha^{-1} post-harvest BA (**Figure 1**). When C subsidy is increased from zero to 25 €/t CO$_2$eq., the best scenario shifts to one with harvesting interval of 20 years and post-harvest BA of 16 m^2 ha^{-1}. Increasing C price further to 50 or 75 €/t CO$_2$eq. increases the harvesting interval further to 30 years.

When the C price is increased, the effect on NPV of each scenario depends on the intensity of the harvests; the more intense the harvests, the more negative the subsidies' effect on the NPV. If the harvests are light enough, the effect of the subsidy system on the NPV is positive. To see how dependent the results are on the interest rate, we set the C subsidy to 50 €/t CO$_2$eq. and vary the interest rate between 1 and 4%. As expected, due to discounting, the higher is the interest rate, the lower is the NPV of all scenarios (**Figure 2**). Increasing interest rate also decreases the differences between scenarios since harvests occurring far later in time are less relevant the higher the interest rate, and when increasing interest rate from 3 to 4% the best scenarios shift to shorter intervals. For instance, from 30-year interval with to 20-year interval, both with 16 m^2 ha^{-1} post-harvest BA from 1 to 3% does not change the best scenario: 30-year interval with 16 m^2 ha^{-1} post-harvest BA produces the highest NPV.

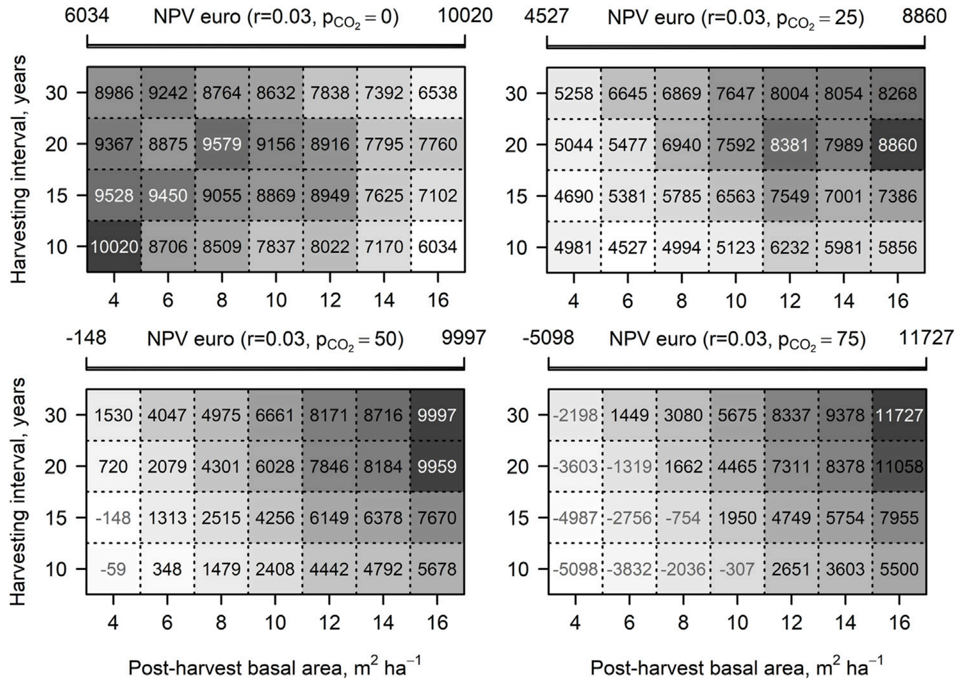
On mineral soil, average stand carbon storage varies between 21 t C and 78 t C ha^{-1} (**Table 1**). Differences in average total soil C (sum of organic layer and topsoil) are roughly the same, varying between 51 t C and 101 t C ha^{-1}. Total discounted carbon fluxes on mineral soil vary from −55 t C ha^{-1} to 19 t C ha^{-1} (**Figure 3**).

Peatland

On peatland, with 3% interest rate and no C pricing the best scenario is with 15-year harvesting interval and 10 m^2 ha^{-1} post-harvest BA (**Figure 4**). The effect of increasing C price is similar to mineral soil; as C price is increased, the scenario with highest NPV has less intensive harvests. Increasing C price to 25 €/t CO$_2$eq, the scenario with highest NPV has interval of 15-year, but the post-harvest BA is increased to 16 m^2 ha^{-1}. Increasing C price further increases the harvesting interval, with the least intensive scenario being the best when C price is 50 €/t CO$_2$eq or higher.

While the C pricing has, similarly to mineral soils, the stronger effect the more intensive the harvests are, the effect on NPV on peatlands is solely negative. Difference in the results between the soil types is due to the soil GHG emissions on peatlands, especially early in the scenarios when ground water level is low.

Increasing interest rate has similar effect as C pricing; the higher the interest rate, the better is the relative profitability of the scenarios of less intensive harvests (**Figure 5**). With 1% interest



NPV euro (r=0.03, $p_{CO_2} = 0$)

Harvesting interval, years	4	6	8	10	12	14	16
30	8986	9242	8764	8632	7838	7392	6538
20	9367	8875	9579	9156	8916	7795	7760
15	9528	9450	9055	8869	8949	7625	7102
10	10020	8706	8509	7837	8022	7170	6034

NPV euro (r=0.03, $p_{CO_2} = 25$)

Harvesting interval, years	4	6	8	10	12	14	16
30	5258	6645	6869	7647	8004	8054	8268
20	5044	5477	6940	7592	8381	7989	8860
15	4690	5381	5785	6563	7549	7001	7386
10	4981	4527	4994	5123	6232	5981	5856

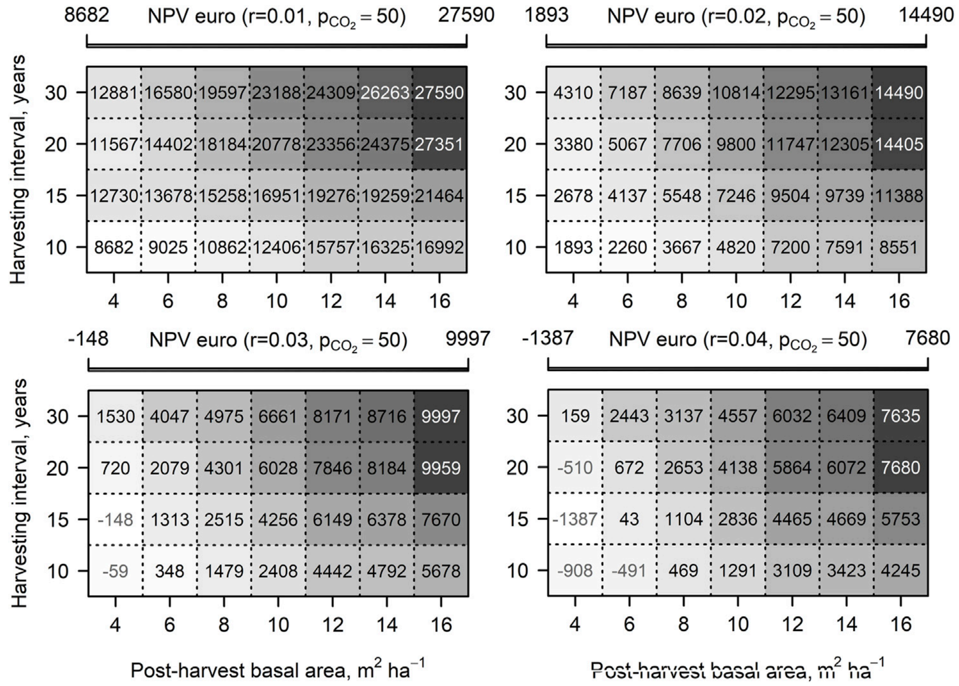
NPV euro (r=0.03, $p_{CO_2} = 50$)

Harvesting interval, years	4	6	8	10	12	14	16
30	1530	4047	4975	6661	8171	8716	9997
20	720	2079	4301	6028	7846	8184	9959
15	-148	1313	2515	4256	6149	6378	7670
10	-59	348	1479	2408	4442	4792	5678

NPV euro (r=0.03, $p_{CO_2} = 75$)

Harvesting interval, years	4	6	8	10	12	14	16
30	-2198	1449	3080	5675	8337	9378	11727
20	-3603	-1319	1662	4465	7311	8378	11058
15	-4987	-2756	-754	1950	4749	5754	7955
10	-5098	-3832	-2036	-307	2651	3603	5500

FIGURE 1 | Net present value (€/ha) of each scenario on mineral soil with 3% interest rate (r) and C price (p_{CO_2}) of 0, 25, 50, and 75 €/t CO_2eq.



NPV euro (r=0.01, $p_{CO_2} = 50$)

Harvesting interval, years	4	6	8	10	12	14	16
30	12881	16580	19597	23188	24309	26263	27590
20	11567	14402	18184	20778	23356	24375	27351
15	12730	13678	15258	16951	19276	19259	21464
10	8682	9025	10862	12406	15757	16325	16992

NPV euro (r=0.02, $p_{CO_2} = 50$)

Harvesting interval, years	4	6	8	10	12	14	16
30	4310	7187	8639	10814	12295	13161	14490
20	3380	5067	7706	9800	11747	12305	14405
15	2678	4137	5548	7246	9504	9739	11388
10	1893	2260	3667	4820	7200	7591	8551

NPV euro (r=0.03, $p_{CO_2} = 50$)

Harvesting interval, years	4	6	8	10	12	14	16
30	1530	4047	4975	6661	8171	8716	9997
20	720	2079	4301	6028	7846	8184	9959
15	-148	1313	2515	4256	6149	6378	7670
10	-59	348	1479	2408	4442	4792	5678

NPV euro (r=0.04, $p_{CO_2} = 50$)

Harvesting interval, years	4	6	8	10	12	14	16
30	159	2443	3137	4557	6032	6409	7635
20	-510	672	2653	4138	5864	6072	7680
15	-1387	43	1104	2836	4465	4669	5753
10	-908	-491	469	1291	3109	3423	4245

FIGURE 2 | Net present value (€/ha) of each scenario on mineral soil with 50 €/CO_2eq. C subsidy (p_{CO_2}) and interest rates (r) of 1, 2, 3, and 4%.

TABLE 1 | Average stand and soil carbon storage (t C) of each scenario on mineral soil. Stand carbon storage is the first number and soil the latter. Harvest interval, HI (in years) in rows, post-harvest basal area, BA (m^2 ha^{-1}) in columns. The highest combined carbon storage presented in bold.

HI \ BA	4	6	8	10	12	14	16
30	38 + 61	45 + 68	51 + 75	58 + 84	66 + 89	73 + 94	**78 + 101**
20	32 + 56	38 + 61	44 + 67	50 + 77	55 + 86	63 + 92	70 + 98
15	27 + 52	32 + 57	38 + 62	43 + 72	50 + 81	56 + 89	60 + 95
10	21 + 51	28 + 56	33 + 61	38 + 70	44 + 80	49 + 86	57 + 92

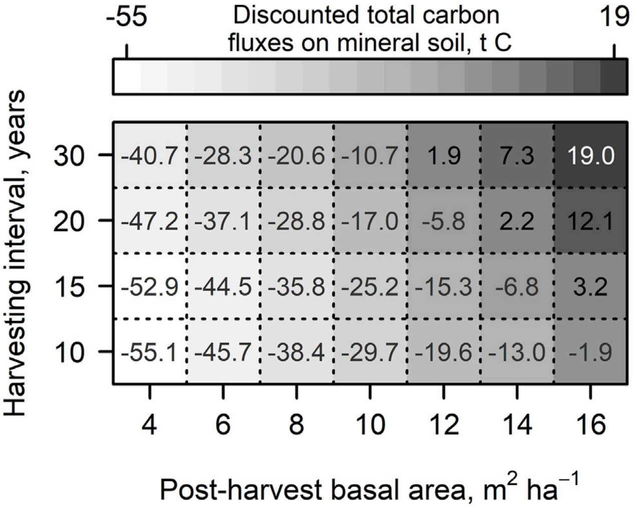


FIGURE 3 | Total discounted C fluxes on peatlands. Discounted with 3% interest rate.

rate, the best scenario uses 15-year rotation with 16 m^2 ha^{-1} post-harvest BA. Increasing the interest rate to 2%, shifts the best scenario to 30-year rotation. Increasing interest rate further strengthens the superiority of the 30-year rotation with 16 m^2 ha^{-1} post-harvest BA.

On peatland, due to the peat C content, the soil C storage vastly exceeds that of stand C (**Table 2**). Average total C storage varies between 1,426 t C and 1,543 t C ha^{-1}, of which soil C accounts for over 95%. While the soil C storage is massive, the differences in the storage between the scenarios are roughly the same as in mineral soils. Total discounted C fluxes on peatland soil vary from −87.5 t C ha^{-1} to −2.6 t C ha^{-1} (**Figure 6**). Due to the heavy first harvest and soil emissions especially early in the scenario when ground water level is low, total discounted changes in C storage is negative for all scenarios.

DISCUSSION

Recent studies (Assmuth and Tahvonen, 2018; Parkatti and Tahvonen, 2021) suggest that CCF outperforms rotation forestry (RF) with low or even moderate social price of C in mineral soils. Further, in RF carbon payments tend to increase optimal rotation period (van Kooten et al., 1995; Pohjola and Valsta, 2007; Juutinen et al., 2018a) while in CCF the transition phase is prolonged (Assmuth and Tahvonen, 2018). In addition, C pricing affects thinnings both in RF and CCF. To date, however, there have not been any studies at stand level comparing the financial performance associated with CCF to mitigate climate change between mineral soils and peatlands. Our simulation study is the first attempt to focus on cost-efficiency of CCF in mitigating climate change both on mineral soils and peatlands. We discovered whether managing forests according to identical CCF either in mineral soils or on peatlands would make any difference with respect to financial incentives for private forest owners to mitigate climate change.

The economic cost of additional C storage (i.e., cost of C abatement) is usually measured as lost timber income (Assmuth and Tahvonen, 2018)[2]. In this study, mineral soil was superior to peatland in cost-efficiency of C abatement. For instance, in peatland the cost of additional ton of CO_2 fluctuated between €30 and €39.5/tCO_2, depending on the C price applied for a private forest owner (€25-€75/tCO_2) while in mineral soil the cost of additional ton of CO_2 was only €2/tCO_2 with a C price of €25/tCO_2, and even turned into a benefit (negative cost of C abatement) when C price was €50 or €75/tCO_2. This indicates a *win-win* situation in which a private forest owner and society both gain when C pricing is being introduced. The former can improve the profitability at stand level and the latter can contribute climate change mitigation by increased C sequestration of trees with costs less than the initial C price paid/subsidized for private forest owners.

Partially the poorer economic performance on peatlands can be explained by initial state. At the beginning of each scenario, the stand is dense and ground water level very low (Juutinen et al., 2021). Because of this, there are large GHG emissions from the soil as the peat decomposes (Shanin et al., 2021). As a result, the C pricing has negative effect of NPV on all peatland scenarios. However, the initial state also harms the C subsidies' effect on NPV on mineral soils, since the first harvest has significant impact also on changes in C storage and discounted C on both site types.

Further, because of this, on peatland the sole timber production (without carbon pricing) was the best choice for a private forest owner while in mineral soil the higher C pricing improved the financial outcome for a private forest owner, with interest rate of 3%. However, while from private forest owner's perspective C pricing has negative effect on economy on

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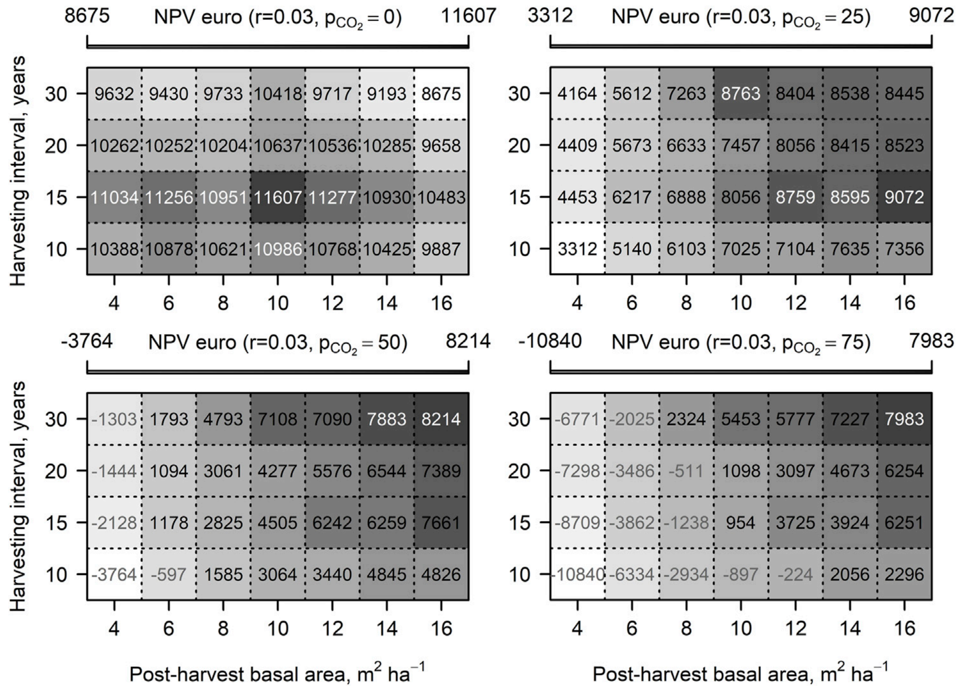
[2] In this study we compared the cost of C abatement between mineral soil and peatland. Technically this was done by first assessing the cost of additional C (expressed as €/tC02) related to a particular CCF with C pricing, compared to the best financial CCF without C pricing.



8675 NPV euro (r=0.03, $p_{CO_2} = 0$) 11607

Harvesting interval, years	4	6	8	10	12	14	16
30	9632	9430	9733	10418	9717	9193	8675
20	10262	10252	10204	10637	10536	10285	9658
15	11034	11256	10951	11607	11277	10930	10483
10	10388	10878	10621	10986	10768	10425	9887

3312 NPV euro (r=0.03, $p_{CO_2} = 25$) 9072

Harvesting interval, years	4	6	8	10	12	14	16
30	4164	5612	7263	8763	8404	8538	8445
20	4409	5673	6633	7457	8056	8415	8523
15	4453	6217	6888	8056	8759	8595	9072
10	3312	5140	6103	7025	7104	7635	7356

-3764 NPV euro (r=0.03, $p_{CO_2} = 50$) 8214

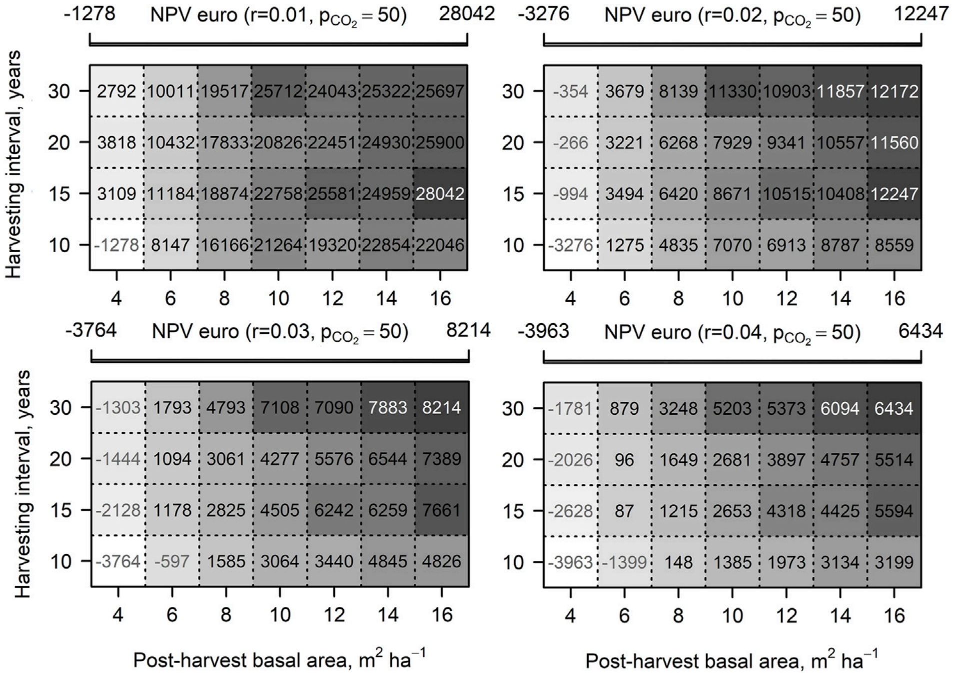
Harvesting interval, years	4	6	8	10	12	14	16
30	-1303	1793	4793	7108	7090	7883	8214
20	-1444	1094	3061	4277	5576	6544	7389
15	-2128	1178	2825	4505	6242	6259	7661
10	-3764	-597	1585	3064	3440	4845	4826

-10840 NPV euro (r=0.03, $p_{CO_2} = 75$) 7983

Harvesting interval, years	4	6	8	10	12	14	16
30	-6771	-2025	2324	5453	5777	7227	7983
20	-7298	-3486	-511	1098	3097	4673	6254
15	-8709	-3862	-1238	954	3725	3924	6251
10	-10840	-6334	-2934	-897	-224	2056	2296

Post-harvest basal area, $m^2\ ha^{-1}$

FIGURE 4 | Net present value (€/ha) of each scenario on peatland with 3% interest rate (r) and CO_2 price (p_{CO_2}) of 0, 25, 50, and 75 €/t CO_2eq.



-1278 NPV euro (r=0.01, $p_{CO_2} = 50$) 28042

Harvesting interval, years	4	6	8	10	12	14	16
30	2792	10011	19517	25712	24043	25322	25697
20	3818	10432	17833	20826	22451	24930	25900
15	3109	11184	18874	22758	25581	24959	28042
10	-1278	8147	16166	21264	19320	22854	22046

-3276 NPV euro (r=0.02, $p_{CO_2} = 50$) 12247

Harvesting interval, years	4	6	8	10	12	14	16
30	-354	3679	8139	11330	10903	11857	12172
20	-266	3221	6268	7929	9341	10557	11560
15	-994	3494	6420	8671	10515	10408	12247
10	-3276	1275	4835	7070	6913	8787	8559

-3764 NPV euro (r=0.03, $p_{CO_2} = 50$) 8214

Harvesting interval, years	4	6	8	10	12	14	16
30	-1303	1793	4793	7108	7090	7883	8214
20	-1444	1094	3061	4277	5576	6544	7389
15	-2128	1178	2825	4505	6242	6259	7661
10	-3764	-597	1585	3064	3440	4845	4826

-3963 NPV euro (r=0.04, $p_{CO_2} = 50$) 6434

Harvesting interval, years	4	6	8	10	12	14	16
30	-1781	879	3248	5203	5373	6094	6434
20	-2026	96	1649	2681	3897	4757	5514
15	-2628	87	1215	2653	4318	4425	5594
10	-3963	-1399	148	1385	1973	3134	3199

Post-harvest basal area, $m^2\ ha^{-1}$

FIGURE 5 | Net present value (€/ha) of each scenario on peatland with 50 €/t CO_2eq. C subsidy (p_{CO_2}) and interest rates (r) of 1, 2, 3, and 4%.

peatlands, for society it is still beneficial, as C pricing changes the best scenario to less intensive management, leading to significant avoided emissions (Figure 8).

An earlier study (Assmuth and Tahvonen, 2018) in mineral soil demonstrated that with increasing C price CCF becomes more profitable than RF, and this holds for interest rates between

TABLE 2 | Average stand and soil carbon storage (t C) of each scenario on peatland. Stand carbon storage is the first number and soil the latter. Harvest interval, HI (in years) in rows, post-harvest basal area, BA (m^2 ha^{-1}) in columns. The highest combined carbon storage presented in bold.

HI \ BA	4	6	8	10	12	14	16
30	31 + 1,413	42 + 1,432	53 + 1,457	63 + 1,474	70 + 1,462	77 + 1,464	**83 + 1,459**
20	23 + 1,423	34 + 1,434	42 + 1,458	50 + 1,466	57 + 1,464	65 + 1,459	72 + 1,463
15	20 + 1,409	29 + 1,432	38 + 1,461	46 + 1,474	53 + 1,478	61 + 1,463	68 + 1,472
10	14 + 1,411	25 + 1,428	33 + 1,466	40 + 1,484	47 + 1,465	54 + 1,473	61 + 1,463

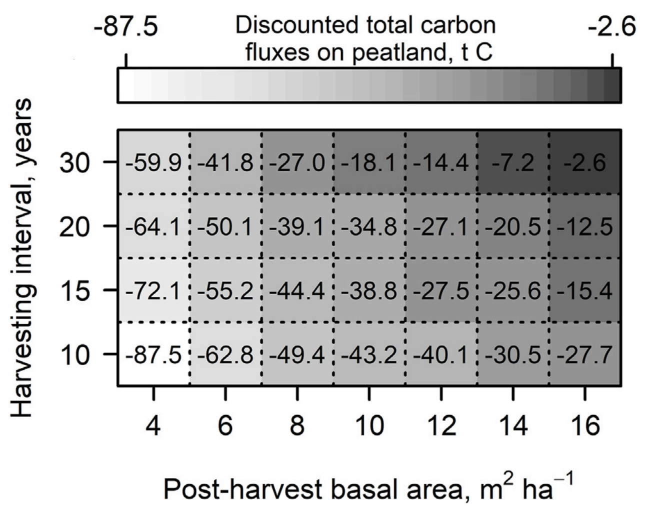


FIGURE 6 | Total discounted C fluxes on peatlands. Discounted with 3% interest rate.

app. 1.5–6%, regeneration costs ranging from ca. 1,000 to 2,500 € ha^{-1}. Another discrepancy between the results of mineral soil and peatland was that with C price at €50/tCO2, in mineral soil the best or second-best performer was always—regardless of the interest rate—a CCF with 30-year harvesting interval and intensity of 16 m^2 ha^{-1} (post-harvest BA) while in peatland the best performer with low interest rates (1 and 2%) was a CCF with 15-year harvesting interval and intensity of 16 m^2 ha^{-1}. These results with relatively mild or moderate harvest intensity (post-harvest BA > 14 m^2 ha^{-1}) are contradicting to earlier studies of financial performance related to CCF on mineral soil (Juutinen et al., 2018b) and on peatland (Juutinen et al., 2021). The difference between this study and earlier studies, however, is due to the inclusion of C pricing which is shown to increase on average the growing stock in optimal CCF management (Parkatti and Tahvonen, 2021).

C pricing has been identified as the most effective strategy to reduce GHG emissions (World Bank Group, 2019), or pricing emissions is at least superior to financial subsidies as long as the C price is high enough to unfold its abatement potential (Gugler et al., 2021). Then, a commonly used cap-and-trade scheme provides a powerful system through which a limited amount of tradable and priced C allowances (cap) is considered for distribution among emitters, and they are further permitted to trade allowances with other emitters, government agencies or brokers (Ji et al., 2017). However, current C pricing mechanism addresses only a small portion of global emission, app. 20% (World Bank Group, 2019) leaving for instance private forests outside the cap-and-trade regulation (Dong et al., 2021). On the other hand, forest could provide a significant contribution to the grand effort needed to mitigate climate change and meet the Paris Agreement targets (e.g., Ekholm, 2020). Therefore, assessing the economic incentives for private forest owners to take part into climate change mitigation is a crucial action prior to initializing a C pricing mechanism to apply private forests. In this study three different C prices were used, namely 25, 50 and 75€/t CO_2eq.—these values can be considered to capture the recent fluctuation of clearing prices for auctions of general allowances of the European Union Emissions Trading System, EU ETS (European Commission, 2021). Furthermore, in the light of recent studies (Ricke et al., 2018; Hintermayer, 2020) future C prices would rise rather than decline—suggesting that our results are cautious with respect to the level of financial incentives.

Prior to concluding the assumptions and constraints applied in this study need to be revealed and discussed. First, the starting point of the analyses was set to a point corresponding to a mature stand with beneficial features for CCF. In other words, the initial state for simulations represents favourable conditions to apply CCF straight away. This reduces generalizability of the results (Sinha et al., 2019 for "dependence of initial state"). On the other hand, such conditions (i.e., mature stands with features favourable for uneven-aged management) are quite common both in mineral soils and on peatlands in Finland. For instance, according to National Forest Inventory (NFI) 12 there are ca. 8.8 and 1.2 million hectares of spruce-dominated forests on mineral soils and peatlands in Southern Finland, respectively (Statistics database 2021, accessed 5 October 2021). Further, approximately 5.6 million hectares in Southern Finland are at least advanced thinning stands (Finnish forest statistics, 2020, Table 1.9) suggesting that there is a considerable amount of—perhaps tens of thousands of hectares—corresponding stands to the initial stand of this study. Second, one limitation of this study is the use of virtual, generated stands instead of replicated empirical stands. However, such an approach (applying virtual or generated stand structure) is commonly applied in stand-level simulation-based economic studies (e.g., Miettinen et al., 2020; Parkatti and Tahvonen, 2021). Furthermore, the key element here is to create as representative stands as possible for simulations (Honkaniemi et al., 2019) rather than rely on a vast number of repeated experiments to cover all possible growth conditions (cf. Tian et al., 2020). Anyway, our results cannot be generalized to stands that have an initial even-aged structure. In this case, it may be optimal to first conduct a clear-cut and then start a conversion towards CCF

(Tahvonen and Rämö, 2016). In addition, our results cannot be generalized to poorer sites, in particular, stands dominated by pine trees that typically benefit from longer harvest intervals than spruce stands in CCF (Parkatti et al., 2019). Then we did not apply a stand-level optimization. This was mainly due to the primary goal of the study: to compare the financial incentives of identical CCF scenarios to mitigate climate change both on mineral soils and on peatlands. In a recent study (Juutinen et al., 2021) similar approach with various combinations of harvest interval and intensity (expressed as post-harvest BA) was applied to discover the profitability of CCF on peatland. Further another recent study (Serrano-Leon et al., 2021) assessed the financial impact of using genetically improved seed material in artificial regeneration in three European countries without applying stand-level optimization. A systematic comparison of alternative potential management regimes by using simulations is therefore a valuable option in many contexts. Finally, stand-level optimization would have resulted most likely different optimal management regimes for mineral soils and peatlands, thus making the comparison between mineral soils and peatlands difficult or even futile.

We conclude that the C pricing encourages milder harvesting in the CCF for both mineral soils and peatlands. However, the effect is stronger on mineral soils, causing significant changes in management already in low C prices. On peatlands, the interplay between stand growth, ground water level and soil GHG balance (Juutinen et al., 2021; Shanin et al., 2021) causes the harvests to be less intensive compared to mineral soils already at 0 C price, thus also the changes from C pricing are less drastic. Then, according to study results C sequestration in mature stands by applying CCF might not be financially lucrative, but in young and developing stands CCF provides financial incentives for private forest owners to participate in climate change mitigation, given the C price stays at low or moderate level. In current *status quo*—in the absence of functioning C credit system—authorities could advise private forest owners how to mitigate climate change cost-efficiently by introducing and providing management alternatives to traditional rotation forestry. Such alternatives, for instance CCF has been proven to be quite beneficial for both climate and private forest owners' finance (Kellomäki et al., 2008; Zubizarreta-Gerendiain et al., 2015).

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

Conceptualization: AA, AJ, JR, VS and RM. Data curation: VS and JR. Formal analysis: AA, JR and AJ. Investigation: AA, AJ and JR. Methodology: AA, JR, AJ and VS. Supervision: RM and AJ. Validation: JR and VS. Visualization: JR. Roles/writing—original draft: AA, AJ and JR. Writing—review and editing: AA, AJ, JR, VS and RM.

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