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Extensification and afforestation of cultivated mineral soil for climate change mitigation in Finland

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ABSTRACT

Offsetting nation-wide CO_2 emissions by carbon sinks from land use change (LUC), e.g. agricultural fields extensification and afforestation, is considered as a major climate change mitigation option. We evaluated the LUC potential for reducing emissions and creating annual soil and ecosystem carbon sinks in Finland. We used agricultural statistics, the forest growth model MOTTI, the soil carbon model Yasso07, and the RCP8.5 climate scenario.

The soil carbon stock (SOC) of extensified grasslands showed on average less carbon loss than cropland, thus reducing future carbon emissions by LUC between 0.17 Mg ha^{-1} y^{-1}, initially, and 0.08 Mg ha^{-1} y^{-1} after 50 years. The annual rate of such carbon gain was in comparison to SOC between 1.4‰ and 0.7‰ which is lower than proposed by the Paris 4‰ initiative for offsetting global anthropogenic CO_2 emissions. Furthermore, after afforestation, estimated SOC is expected to increase above pre-LUC levels with 30 years lag. Estimated SOC sink from afforestation when compared to continuous cultivation varied depending on dominant tree species and soil fertility from between 0.19 Mg ha^{-1} y^{-1} (1.7‰ for spruce in medium fertile soil) to 0.46 Mg ha^{-1} y^{-1} (3.7‰ for silver birch in highly fertile soil). Future total soil and biomass carbon sink attributed to afforestation ranged between 1.65 and 2.44 Mg ha^{-1} y^{-1}.

Combined carbon sinks created by the present LUC could with 30 years lag offset annually between 0.01 and 4% of the present national net CO_2 emissions in Finland. The long delay and a small scale of potential future carbon emission reduction by the LUC highlighted the importance of employing additional tools to reach the national neutrality targets due in next 15 or 30 years.

1. Introduction

The Paris climate agreement has set a target to reduce greenhouse emissions to levels that will limit global temperature increase to 1.5°Celsius above pre-industrial levels (UNFCCC, 2015), which requires emission reductions by about 45% from 2010 levels by 2030 and reaching net zero emissions by around 2050 (IPCC, 2018a; IPCC, 2018b). Strategies to achieve this goal include improved climate-smart land management approaches such as different combinations of reforestation, afforestation, reduced deforestation, and utilization of bioenergy alternatives (IPCC, 2019a). Understanding the role of LUC in increasing SOC stock in different regions and at varying fertility levels promotes the development of climate-smart management and land use strategies.

Current cultivation practices typically lead to loss of soil organic carbon (SOC) (Sanderman et al., 2017; Heikkinen et al., 2013) as is reflected by greenhouse gas emissions reported in the national greenhouse gas inventories (UNFCCC, 2019). The carbon balance of croplands may be improved by better cultivation approaches (Paustian et al., 2016; Tao et al., 2019), with fields demonstrating persistent low productivity expected to act as carbon sources should they remain in cultivation (Peltonen-Sainio et al., 2019). Considering not only differences in productivity, but also logistic advantages of field parcels with respect to land allocation, allows for sustainability assessment and aids in the development of schemes addressed at agricultural intensification and the eventual reduction of cropland areas without posing risk to food security. Options for the utilization of excess areas include extensification of cropland to grassland as well as afforestation (Peltonen-

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Sainio et al., 2019).

Empirical studies of SOC changes resulting from extensification and afforestation provide conflicting results; both increased and decreased soil carbon levels have been shown to occur after land use change (LUC) (Laganière et al., 2010; Poeplau et al., 2011; Karhu et al., 2011; Heikkinen et al., 2014). Interpretation of these results has been hindered by relatively small SOC changes in large and highly variable SOC stocks observed over relatively short (decadal) time steps (Lehtonen and Heikkinen 2015). For this reason, soil carbon models based on mechanistic processes of decomposition and sequestration such as Yasso07 (Tuomi et al., 2011), CENTURY (Parton et al., 2015), ROMUL (Chertov et al., 2001), RothC (Coleman and Jenkinson, 1996) and Biome-BGC (Thornton 1998) are widely used to predict changes in SOC after LUC. The Yasso07 soil carbon model (Tuomi et al., 2011) has been listed among other models as a potential tool for national greenhouse gas reporting to the UNFCCC (IPCC, 2019b) and is used by several European countries (UNFCCC, 2019). It has been widely applied in SOC simulations of agricultural (Karhu et al., 2011; Palosuo et al., 2015; Heikkinen et al., 2014) and forest soils (Lehtonen et al., 2016; Ťupek et al., 2019; Hernández et al., 2017).

This study aims to estimate the nation-wide potential of improving land carbon balance over the next 50 years by following a planned 2020 – 2030 conversion of a portion of current mineral soil croplands to extensive grasslands and forests. The effects of continuous cultivation (business as usual, BAU) on the rate of SOC stock change versus LUC were examined using the Yasso07 soil carbon model. Modelled rates of SOC change were applied to LUC area scenarios at different levels of ambition. Specific aims were to determine differences in SOC rate changes between 1) tree species used (Norway spruce (*Picea abies*, (L.) H. Karst) vs. silver birch (*Betula pendula*, Roth.)), and 2) high and medium soil site fertility levels. The impact of regional climatic conditions on SOC changes and biomass production due to the LUC were also assessed.

We hypothesized that afforestation by Norway spruce would yield a higher rate of soil carbon accumulation than that of silver birch and that highly fertile soil would show greater soil carbon gains due to differences in biomass production. Furthermore, higher rates of soil carbon accumulation after afforestation in southern Finland were expected than in northern regions due to differences in biomass production and enhanced decomposition due to warmer climates.

2. Methods

2.1. Estimates of land area for extensification and afforestation

To estimate potential nation-wide set-aside extensification and afforestation areas, Finland was divided into three geographical regions (South, North-East, and North-West) composed of 16 sub-regions (corresponding to Finnish ELY centres for economic development, transport, and the environment) (Fig. 1). Cultivated field parcels in these regions were classified into three categories: sustainably intensified fields for increased food production and those allocated for either extensification or afforestation. This categorization was based on an optimization tool developed for land use planning and available from Luke's EconomyDoctor-portal for Finnish farmers (Peltonen-Sainio et al., 2019) (Table 1). Within the tool, field parcel classification is determined based on the parcel size, distance from the farm centre, geometric shape, slope, productivity, proximity to waterways, soil type, and logistic advantages. Lower and the upper ranges in identified areas for years 2020–2100 were derived by dividing or multiplying the area, suggested by the tool, by two. This accounted for uncertainty in future LUC, depending on policies that may lead to lower or higher shares of extensified and afforested fields than those proposed for the period 2020–2030 by the land-use optimization tools with its current target settings. The soil and biomass model simulations were applied to these areas to estimate effects of LUC should farmers implement the proposed changes.

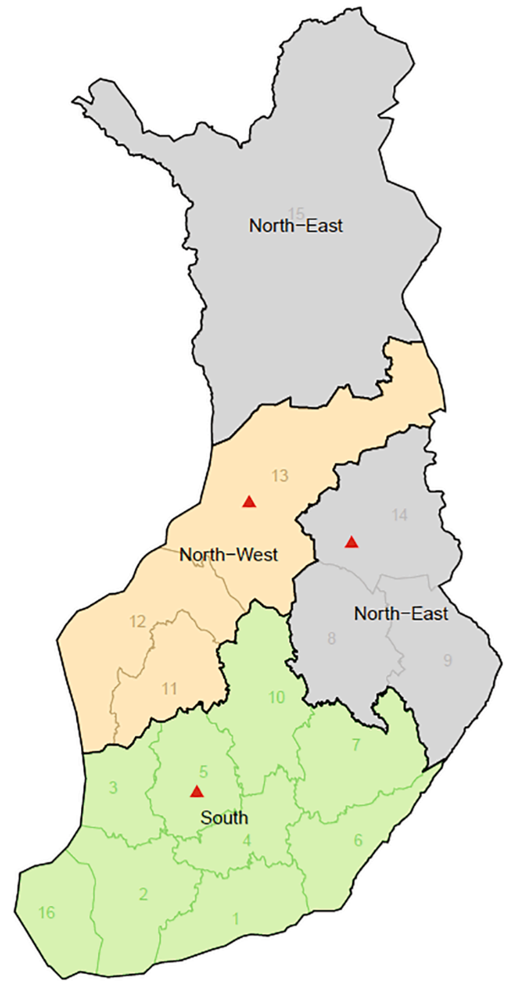

Fig. 1. Outlines of three geographic regions (South, North-East, and North-West) in Finland based on 16 centres for economic development, transport, and the environment (ELY centres). Triangles show the locations of weather stations with representative region climates. The largest potential for LUC is in South and lowest in North-East (Table 1).

Table 1
Estimated area (ha) of land use change (LUC) in 2020–2030 based on the land use optimization tool (Peltonen-Sainio et al., 2019).

Region	LUC					
	Cropland to grassland		Cropland to forest		Grassland to forest	
	ha	%	ha	%	ha	%
South	11,935	64	1782	69	1976	83
North-East	2814	15	149	6	125	5
North-West	3943	21	650	25	283	12
Total LUC	18,693	100	2580	100	2383	100
Total Arable land	2,246,000					
LUC / Arable land		0.83%		0.11%		0.11%

2.2. Soil and biomass carbon modelling

SOC stock changes during the period 1900 to 2100 were modelled using the Yasso07 soil carbon model (Tuomi et al., 2009, 2011) in accordance with the Finnish greenhouse gas inventory method (Statistics Finland, 2020). Input parameters included climate (monthly temperature and precipitation) and agricultural or forest litter data for three ELY sub-regions (Pirkanmaa, Kainuu, and Pohjois-Pohjanmaa) (Fig. 1). Due to their typical environmental conditions, Pirkanmaa represented

Southern Finland whereas Kainuu and Pohjois-Pohjanmaa represented North-East and North-West Finland, respectively. SOC modelling scenarios included three types of agricultural lands (food and feed cropland, managed grassland, and extensive grassland) and whether they were afforested by Norway spruce or silver birch on fertile and medium-fertility soil (corresponding to herb-rich and mesic forest types (Hotanen et al., 2008) (Table 2). Croplands in Finland include grasslands used for feed production defined as extensive grasslands such as set-aside areas and buffer zones. Afforestation of cropland was alternatively evaluated considering whether it occurred on a bare fallow or was converted to grassland beforehand. Cultivation of crops was associated with fertile soil and grass with soil having a medium nutrient status. Our simulations assumed that cropland was initially relatively fertile herb-rich forest while grassland was originally mesic forest.

Estimates of SOC stocks were compared with SOC data acquired from published literature. Modelled SOC stocks after 100 years of cultivation used in our study were compared with mean SOC stock observations to a depth of 15 cm and their confidence intervals (Heikkinen et al., (2013) as cited by Palosuo et al. (2015)) scaled to 1 m depth for the Pirkanmaa, Pohjois-Pohjanmaa, and Kainuu regions (Palosuo et al., 2015). Modelled deforestation SOCs were also compared with deforestation soil carbon stock data obtained from Karhu et al., (2011). Although these data represented soils from 7 to 29 years after managed forest clearing in Southern Finland in 1990, they could not be compared to the period after 1900 and so were instead compared to the period after 1990. This is because SOC rate change is dependent on SOC stock and managed forests have typically lower SOC than natural forest in equilibrium due to loss after clearing and removal of biomass (Mayer et al. 2020). Modelled SOCs after afforestation were compared with Karhu et al., (2011) afforestation data from sites planted with spruce and birch in Southern Finland based on relative changes in SOC prior to afforestation in 1990 and 17–18 years after.

2.3. Yasso07 model runs

The Yasso07 soil carbon model (Tuomi et al., 2009; 2011) is one of the most widely applied SOC models in Europe. It has been extensively calibrated using mostly European, North and South American litter bag, wood decay and SOC measurements (Tuomi et al., 2009). The source code of the model used in this study was built in R software environment (R Core Team 2017) on the SoilR platform package (Sierra et al., 2012) based on the mathematical description and parameters of Tuomi et al. (2011). The model runs on annual time steps with data inputs of litterfall, including size, chemical composition, annual temperature, monthly temperature amplitude, and precipitation. Climate variables (annual air temperature and precipitation) control decomposition and transfer rates of organic matter between five pools characterized by the solubility of the organic material as acid- (A), water- (W), ethanol- (E) soluble pools, non-soluble pool (N), and passive humus pool (H). Yasso07 estimates SOC stock and SOC changes to a depth of 1 m (organic and mineral layers). We simulated forest equilibrium SOC stock at year 1900 (x) analytically (Eq. (1), Sierra et al., 2018) using:

$$x = -\xi B^{-1}\bar{u} \tag{1}$$

where B is the inverse of the Yasso07 model structural matrix, ξ is the climate modifier and $\bar{u}$ is the litter input (including mean annual litter of roots, stump, branches, foliage, understory, and mean annual stem increment over one rotation period). The global parameter values of decomposition rates, flow rates, and other dependencies were adopted from Tuomi et al. (2011). Following year 1900 we continued to run Yasso07 at annual time steps for a series of different climate and litter scenarios.

Table 2
Land use scenarios evaluated in this study.

Past land use	Soil nutrient status	Land use change (LUC)	Future land use
Cropland[a]	High	Afforestation	Norway spruce forest [c]
		Afforestation	Silver birch forest [c]
		Extensification	Grassland
		no LUC [d]	Cropland
Grassland[b]	Medium	Afforestation	Norway spruce forest
		Afforestation	Silver birch forest
		no LUC [d]	Grassland

[a] cropland in Finland includes feed production on managed grassland.
[b] grassland includes extensive grassland such as areas set-aside, buffer zones etc.
[c] afforestation on cropland was alternatively evaluated using either conversion from managed grassland or of bare fallow.
[d] no LUC referred later as business as usual (BAU).

2.4. Climate

We used air temperature and precipitation data provided by the Finnish meteorological institute from weather stations nearest to the municipalities of Tampere (Southern region), Kajaani (North-East region), and Siikajoki (North-West region) (Fig. 1 and Fig. S1, Venälainen et al., 2015 as representative regional data. Information obtained from 1.1.1960 to 31.12.2017 was aggregated from monthly to annual levels to estimate mean annual temperature, minimum and maximum monthly temperature, and annual precipitation sum (Fig. S1) and used as Yasso07 inputs. For the 1900 – 1960 period we extrapolated observed trends according to Aalto et al. (2016) with temperature and precipitation increases of + 0.1 °C and + 3 mm per decade, with future climate trends (2018–2100) modelled according to Ruosteenoja, 2016 and scenario IPCC RCP8.5 (Fig. S1). These projections were based on the ensemble of 35 recent-generation (CMIP5) global climate models. Overall, the annual temperature increased by 5 °C and precipitation by 20% in the projection from the present up until the end of year 2100 (Fig. S1). However, in Yasso07 soil carbon model (Tuomi et al. 2011) the main driver of the soil organic matter decomposition and consequently CO_2 emissions is the change in the litter input. This was in our study represented by the lower input from agriculture than from forestry (Fig. S2). With relatively small temperature differences in scenarios before 2050, 0.3°Celsius for 2050 and 1.0 °C for 2070 (Ruosteenoja, 2016, Fig. S1) their impact on simulated SOC stock changes was lower in comparison to relatively larger difference in litter input after LUC.

To support the policy decisions in reaching carbon neutrality targets on the short time scales (2035 for Finland and 2050 for EU), the use of RCP8.5 compared to RCP4.5 is more reasonable due to RCP8.5 showing the closest agreement (1%) with the historic 2005–2020 CO2 emissions (Schwalm et al. 2020). Furthermore, after 2050 RCP4.5 could be too optimistic, due to RCP4.5 missing emissions from the natural feedbacks accelerating climate warming (Schwalm et al. 2020) such as CO_2 release from extreme wildfires (Witze 2020, Che Azmi et al. 2021, Shiraishi and Hirata 2021) and CH_4 release from permafrost thawing (Froitzheim et al. 2021).

2.5. Estimation of biomass production and litter input to soil

Forest litter input (Figs. S2 and S3) was based on forest biomass modelled by the MOTTI stand simulator (Hynynen et al., 2014, 2015, Siipilehto, 2014), and litter components (including fine- and coarse-roots, stump, branches, foliage, and understory) (Table S1) were estimated as in Lehtonen et al. (2016). We estimated forest biomass specific for species (2), soil fertility types (2) and regions (3) for a total of 12 forest stands during one rotation period (typically more than 50 years). Stand growth was modelled using MOTTI and was based on stand- and tree-level development with yields specific to forest sites with defined soil fertility classes and locations. Silvicultural practices (eg. planting density, survival, soil preparation, and juvenile stand management) and thinnings were carried out according to Finnish silvicultural guidelines (Rantala, 2011). Biomass composed of stems, branches, needles/leaves, stumps, and coarse roots was predicted using the models of Repola (2008, 2009). Fine root biomass was estimated according to the birch and C/N ratio dependent model developed by Lehtonen et al. (2016). For 1900 equilibrium forest SOC simulations we used mean forest litter over the same rotation period as described above allowing for a large ± 25% uncertainty due to limited information available for the past millennium of land use. Litter input after afforestation in year 2017 followed the development of managed forest stand for one rotation period. Understory litter from the conversion of managed and extensive grasslands to forest resulted in increased grass litter. This was in contrast to afforestation of bare fallow where mean forest understory litter levels (Table 1, Fig. S2) comprised just half of the combined litter. Furthermore, grass litter input was dependent on forest canopy, decreasing from maximum levels at the year of afforestation, to zero by completion of half of the forest rotation period (Fig. S2). To cover uncertainty related to regional forest production and changing climate we allowed for ± 30% variation in present and future forest stand litter input (Lehtonen and Heikkinen, 2015; Sievänen et al., 2014).

Agricultural plant litter input over the 1990 – 2016 period for grassland (mean 3.2 Mg ha^{-1}) and cropland (mean 2.7 Mg ha^{-1}) (Fig. S2 and S3) was the same for different regions in Finland and was adopted from Palosuo et al. (2015) where litter inputs for different crops were estimated based on regional crop yields using constant biomass allocation factors. This approach was originally proposed by Bolinder et al. (2007). To account for uncertainties related to the estimation of agricultural litter inputs we attributed ± 10% uncertainty to cropland and grassland litter. This value was based on an observed standard deviation of inter-annual variation of cropland litter (5%), and variation in litter quality (5–10%, Karhu et al. (2012)). For future remaining cropland and grassland, we used mean litter input and the same uncertainty as between 1990 and 2016. The agricultural litter input between 1901 and 1990 increased by 67% according to the trend based on historical records as cited by Karhu et al. (2011). Cropland and grassland litter input in 1901 was attributed with ± 50% uncertainty which linearly decreased towards ± 10% uncertainty for observations in 1990 (Fig. S2 and S3).

3. Results

3.1. Carbon loss due to deforestation and cultivation

Following deforestation and during subsequent cropland cultivation between 1900 and 2017, Finnish soils lost 116 Mg ha^{-1} from highly fertile croplands in both South and North-West regions alike and 67 Mg ha^{-1} from mid fertile grasslands in the North-East (Fig. 2, Fig. S4). Uncertainty bounds for cropland and grassland overlapped. SOC originating from woody litter before cultivation was continuously depleted during cultivation whereas that derived from non-woody plant litter was maintained at similar levels (Fig. 2a). Forest and cultivated land non-woody litter inputs were also comparable.

Modelled SOC stocks following 100 years of cultivation were within the uncertainty range of mean upper soil layer SOC stock observations scaled to 1 m (Palosuo et al. (2015)) (Fig. 2, Fig. S4). SOC loss rates reflected SOC magnitude; the loss being most rapid immediately after deforestation for equilibrium SOCs in 1900 and slowest during the later period of cultivation (Fig. 3a). Loss calculated as the running mean of annual SOC change ($\Delta\overline{SOC}$) in Southern Finland was after 5 years in 1905 as high as 2.2 and 1.6 Mg ha^{-1} y^{-1} (for croplands and grasslands respectively) but over 100 years declined to 1.0 Mg ha^{-1} y^{-1}. When evaluating only the 1990–2017 period, $\Delta\overline{SOC}$ of cultivated land was −0.5 ± 0.37 (±SD) and −0.45 ± 0.29 Mg ha^{-1} y^{-1}, comparable to deforestation observations reported in Karhu et al. (2011). The simulated SOC loss rates for the next 50 years of continuous cultivation decreased slightly to 0.40 and 0.37 Mg ha^{-1} y^{-1} which is equivalent to a future SOC loss of 20 and 18 Mg ha^{-1} compared with the present state (Fig. 3b).

3.2. SOC benefit below 4‰ from cropland conversion to extensive grassland

In the case of cropland extensification (LUC from cropland to extensive grassland), SOC loss would be smaller than for continuously cultivated cropland (Fig. 3b). Thus, the difference between the lower SOC loss resulting from LUC and higher SOC loss due to no LUC (business as usual) would result in a future positive SOC gain. However, the rate of soil carbon accumulation arising from extensification would decrease over time. In the South it would change between 0.17 Mg ha^{-1} y^{-1} after 10 years and 0.08 Mg ha^{-1} y^{-1} after 50 years (Figs. 4 and 5) which in the scale of the present cropland's SOC stock 123 Mg ha^{-1}

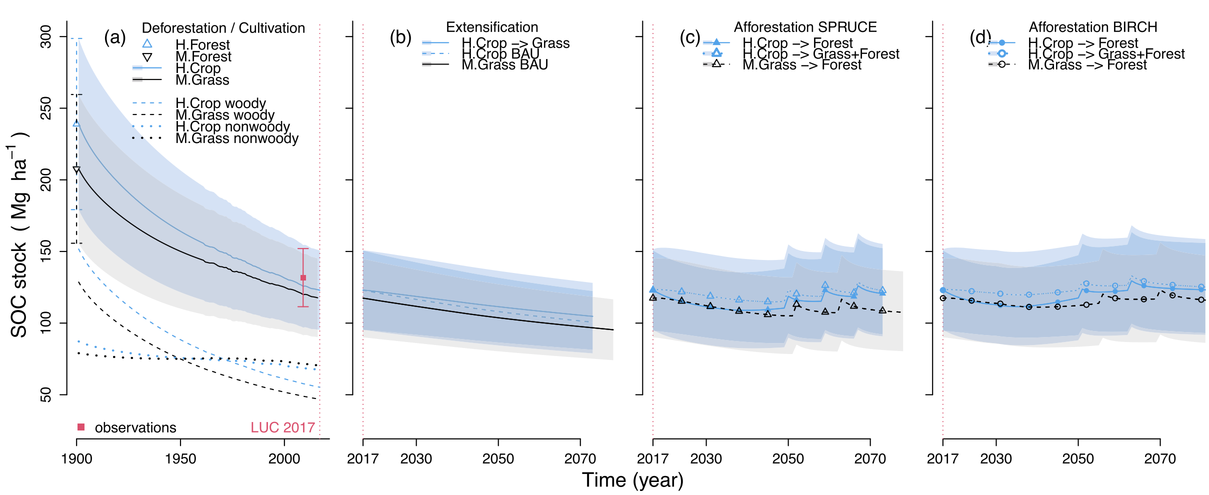

Fig. 2. Modelled SOC (Mg ha^{-1}) for Southern Finland (a) after deforestation in 1900 and during the cultivation period 1901 – 2017; and (b, c, d) after the land use change (LUC) in 2017 including (b) extensification to grassland and continuous cultivation (business as usual, BAU), (c) afforestation with spruce, and (d) afforestation with birch. The cropland was afforested on the bare fallow (Crop -> Forest) or on managed grassland (Crop -> Grass + Forest). (H) is highly fertile land and (M) is medium fertile land. Blue and gray shaded areas denote uncertainty estimates of the modelled values. Red dot with error bar denotes mean and standard error of the scaled SOC observations to 1 m from depth of 15 cm and their confidence intervals (Heikkinen et al. (2013) as cited by Palosuo et al. (2015)).

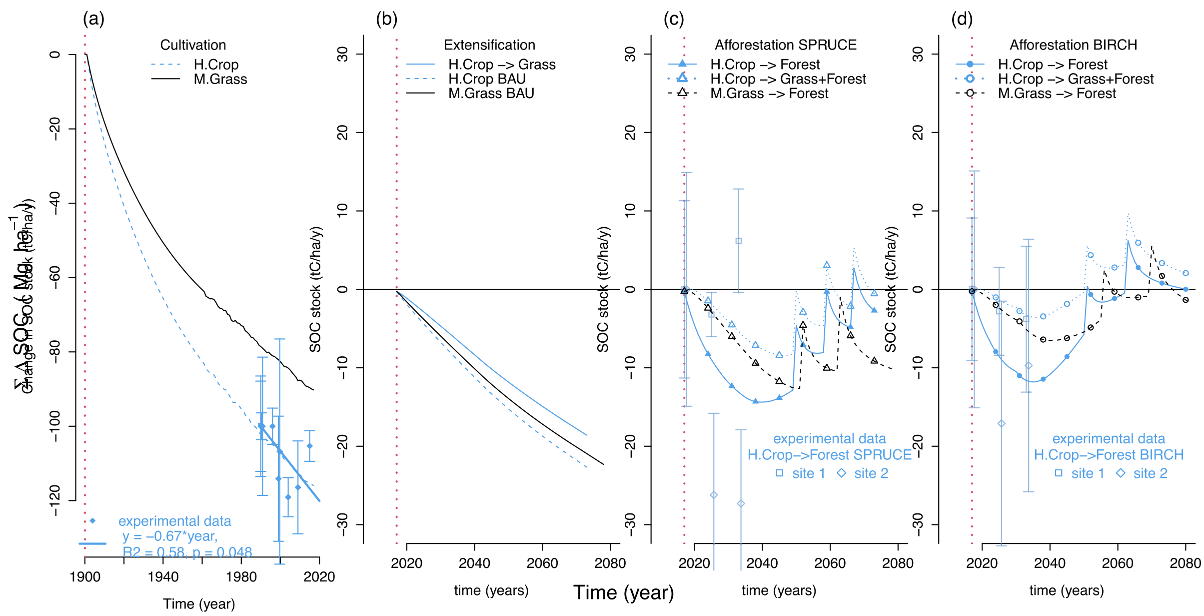

Fig. 3. Modelled cumulative SOC change (ΣΔSOC in Mg ha^{-1}) for Southern Finland SOC before and after land use change (LUC, red vertical line). Experimental deforestation and afforestation data from bare fallow experiment (c, d) were taken from Karhu et al. (2011). For more details see section on soil and biomass carbon modelling. (H) is highly fertile land and (M) is medium fertile land.

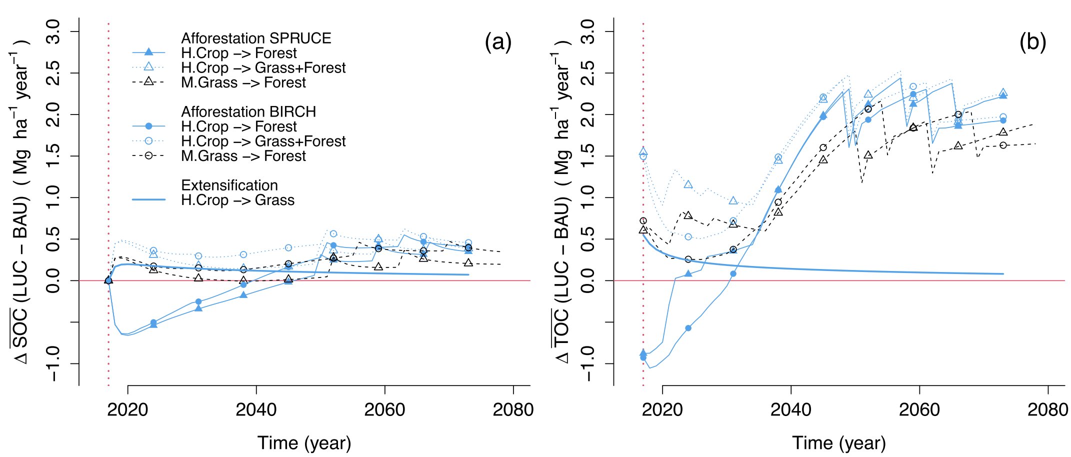

Fig. 4. Modelled mean annual organic carbon stock (Mg ha^{-1} year^{-1}) change (a) in soil ($\Delta\overline{SOC}$), and (b) in soil and biomass combined ($\Delta\overline{TOC}$) for Southern Finland after land use change (LUC) in 2017. The change was estimated as the difference between carbon stocks after LUC and those of business as usual (BAU). (H) is highly fertile land and (M) is medium fertile land.

corresponds to rates of 1.4‰ and 0.7‰. This is approximately the same across regions due to the assumption of similar biomass production (Fig. S3).

3.3. Afforestation by Norway spruce provided no or negligible soil carbon sink

Only highly fertile cropland soils afforested by Norway spruce would accumulate more carbon than before LUC and only for a short period of time, after 34 or 43 years following increased litter spikes after thinning (Fig. 3c). At the end of forest rotation, when mature forest trees are felled, the final SOC balance would be negligible. Medium fertility soils of extensified grassland afforested with Norway spruce will continue to lose carbon (Fig. 3c). The final cumulative SOC change (ΣΔSOC in Mg ha^{-1}) after one forest rotation varied depending on soil fertility levels as well as management types. This was determined to be −1.9 Mg ha^{-1} for afforested highly fertile cropland on bare fallow, 0.3 Mg ha^{-1} for cropland with grass cover and −9.3 Mg ha^{-1} for afforested extensified grassland on medium fertility soil (Fig. 3c).

3.4. Afforestation by silver birch created soil carbon sink

Simulated SOC change after afforestation (Fig. 3) was mainly attributed to plant cover and its resulting litter contribution (Fig. S2). Primary differences in litter input resulted from variations between tree species, soil nutrient status, and afforestation scenarios. Afforestation on bare fallow during the preceding 30 years resulted in higher SOC loss rates than those caused by cultivation (Fig. 3f) as during the first decade litter input originating from planted tree seedlings was lower than that derived from crop residues (Fig. S2). However, afforestation on cropland covered with grass provided more litter input than that produced from cultivation, with a slight reduction of SOC (Fig. 3). Difference attributed to management type (cropland afforestation on bare fallow or on grass) was largest after LUC and diminished towards the end of the forest rotation period as tree litter dominated carbon soil input.

Highly fertile cropland soils afforested on bare fallow and grassland

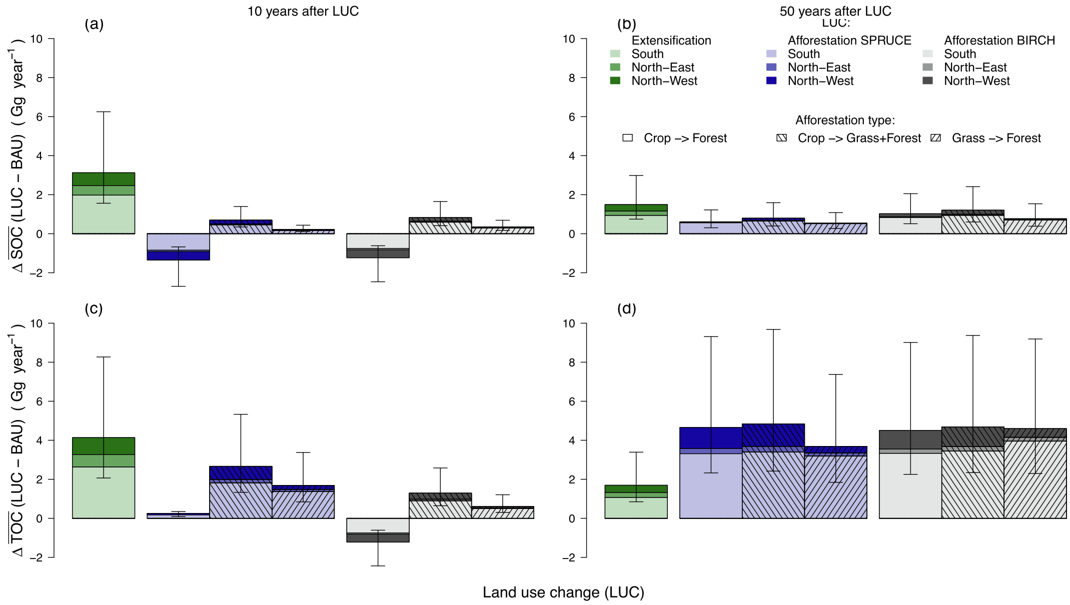

Fig. 5. Finnish regional (South, North-East, North-West) estimates of mean annual potential organic carbon stock (Gg C year^{-1}) change in soil ($\Delta\overline{SOC}$, panels a, b) and in total ($\Delta\overline{TOC}$, soil and biomass combined, panels c and d) 10 years (a, c) and 50 years (b, d) after the land use change (LUC) in 2017. The change was estimated as the difference between carbon stocks after LUC and those of business as usual (BAU) multiplied by the total area proposed for LUC by the land optimization tool. The error bars show the uncertainty in future area of LUC. Individual values can be found in Table S2.

by silver birch in South Finland became SOC sinks after 32 and 35 years, and medium fertile afforested soils of extensive grassland after 40 years (Fig. 3d). Only afforested croplands remained SOC sinks thereafter, and at the end of forest rotation (before mature forest is harvested), their final balance depending on management type was 0.7 Mg ha^{-1} or 2.8 Mg ha^{-1} (Fig. 3d).

The SOC sinks created by silver birch and not by Norway spruce afforestation resulted from their slightly larger non-woody contribution. Our models found total forest biomass to be greater for spruce than birch, with birch fine-root litter being approximately one third larger than spruce, and foliar litter input also larger.

3.5. SOC and TOC benefits by afforestation

SOC gains from afforestation (the difference between ΔSOC_{LUC} and ΔSOC_{BAU}) in Southern Finland at the time before final harvest ranged between 22 and 12 Mg ha^{-1} for spruce and between 26 and 22 Mg ha^{-1} for birch (depending on soil fertility and management type) (Fig. S5). The time of final harvest varied depending on soil fertility; 57 years for highly fertile soil and 64 years for medium fertile soils. The mean annual rate of SOC gains by afforestation ($\Delta\overline{SOC}$) varied for spruce between 0.19 and 0.43 Mg ha^{-1} y^{-1} and for birch between 0.35 and 0.46 Mg ha^{-1} y^{-1} (Fig. 4). Scaled SOC stock levels before LUC were found to be 117 Mg ha^{-1} for medium fertile soil and 123 Mg ha^{-1} for highly fertile soil. The scaled SOC accumulation rates at the end of first forest rotation varied between 1.7‰ and 3.3‰ for spruce and between 3.0‰ and 3.7‰ for birch.

If plant biomass carbon (BOC) was accounted for in addition to SOC, total organic carbon (TOC) gains after afforestation and forest rotation (the difference between ΔTOC_{LUC} and ΔTOC_{BAU}) ranged from 117 to 129 t C ha^{-1} for spruce and from 102 to 113 Mg ha^{-1} for birch (depending on soil fertility and management type) (Fig. S5). As most carbon gain was incorporated into biomass, the mean annual afforestation rates of TOC gain ($\Delta\overline{TOC}$) varied between 1.9 and 2.3 Mg ha^{-1} y^{-1} for spruce and between 1.7 and 2.0 Mg ha^{-1} y^{-1} for birch (Fig. 4). TOC stock levels before LUC were 120 Mg ha^{-1} for extensive grasslands developed on medium fertile soil and 125.5 Mg ha^{-1} for croplands cultivated on highly fertile soil, with scaled TOC accumulation rates at the end of the first forest rotation varying between 15.8‰ and 18.3‰ for spruce and between 14.1‰ and 15.9‰ for birch.

3.6. Regional and national carbon sequestration potential

In the short term, 10 years after LUC, the extensification of cropland would, in the whole of Finland, result in a larger carbon storage potential (3.1 Gg year^{-1} to SOC, 1 Gg = 10e9 g) than that resulting from afforestation with SOC potential changes ranging from −1.3 Gg year^{-1} to 0.8 Gg year^{-1}, depending on soil fertility and management type (Fig. 5, Table S2). The greater carbon gain from extensification of cropland was due to a slightly higher litter input distributed over a large spatial area (18.7 thousands ha, 0.83% of arable land) as opposed to that caused by a higher litter input over a four times smaller area of (4.9 thousands ha, 0.22% of arable land) (Table 1). SOC sequestration would be larger in the South than in the North-East and North-West due to increased sequestration rates and a larger LUC area (Fig. S4, Table 1). However, in the long term, 50 years after LUC, carbon storage potential resulting from extensification (1.52 Gg year^{-1} to SOC) would be lower than that resulting from afforestation by silver birch of croplands and extensified grasslands combined (2.0 Gg year^{-1} to SOC) (Fig. 5, Table S2). When TOC is considered, after 50 years of both cropland and grassland afforestation, Finland will gain significant carbon storage potential (9.3 Gg year^{-1} for silver birch and 8.5 Gg year^{-1} for Norway spruce compared with 1.7 Gg year^{-1} for extensification) (Fig. 5, Table S2).

4. Discussion

4.1. Climate change mitigation by land-use change

Our results show that mineral soil croplands, which are currently greenhouse gas (GHG) emission sources, can be converted into relatively strong carbon sinks by afforestation with either Norway spruce or silver birch. Land use optimization, when based on a process understanding of the organic matter decomposition and soil carbon sequestration, has long been recognized as a means by which climate change mitigation can be put into practice (Smith et al., 2005; Scharlemann et al., 2014).

Differences in SOC loss rates between extensified cropland and remaining cropland soil would gradually decrease from 0.17 Mg ha^{-1} y^{-1} after 10 years to 0.08 Mg ha^{-1} y^{-1} over 50 years. However, the resulting annual carbon emission reduction rate of between 1.4‰ to 0.7‰ and would not be enough to reach the ambitious “4 per 1000” annual soil carbon sequestration target proposed to UNFCCC as one solution to alleviate climate change (Lal, 2016). Furthermore, it is also unlikely that increased future agricultural yields and residues from croplands remaining in food production would ensure an annual 4‰ increase in SOC. As soil carbon degradation in cultivated soils is due to depleting SOC originating from woody litter input (Fig. 2), ways to replenish this source should be evaluated. It is known that woody biochar may enhance soil carbon sequestration while also improving soil structure, microbial diversity, nutrient and water retention (Gul et al., 2015; Hansen et al., 2014; Paustian et al., 2016; Smith, 2016; Zhao et al., 2019). A combination of carbon sink management practices such as biochar application, cover cropping, and mulch farming would be needed in addition to extensification in order to attain an annual 4‰ SOC gain (Smith et al., 2016; Lal, 2016; Minasny et al., 2017).

In contrast, the positive difference between SOC of afforested and cultivated land, i.e. the total afforestation SOC sink would, in Southern Finland, over one rotation period of managed forest (approximately 60 years) range from 12 Mg ha^{-1} (Norway spruce afforestation of medium fertile extensive grassland) to 26 Mg ha^{-1} (silver birch afforestation of highly fertile managed grassland). When biomass carbon is considered, total forest carbon sink would then range from 102 Mg ha^{-1} (silver birch afforestation of medium fertile extensive grassland) to 129 Mg ha^{-1} (Norway spruce afforestation of highly fertile managed grassland). The largest annual rates of total carbon sink associated with afforestation were between 1.7 and 2.3 Mg ha^{-1} y^{-1} and took place with an approximate 30-year delay in relation to the maximum forest growth period and remained at similar levels until the end of the rotation period (Fig. 4). The annual total carbon sink rates of Norway spruce afforestation in this study in Finland were slightly lower, and the delay was longer, compared to a similar study in Norway (Bright et al., 2020). Following the first rotation, forest carbon sink would be dependent on future management intensity. The carbon sink of forest stand biomass may be reversible (accumulated biomass carbon may return to the atmosphere) in the case of deforestation, natural disturbances (windthrows, wildfires, insect outbreaks or diseases) or should harvesting intensity be higher than the growth increment (Nabuurs et al., 2013).

However, should land use of afforested fields remain constant, despite undergoing regular clear-cut harvesting and subsequent regeneration, tree stand biomass carbon sink benefit would be retained at close to average levels with dead roots , stumps and other woody debris amending the SOC stock. The clear cut harvesting would reduce total carbon sink by approximately 30% in comparison of sustaining continuous cover forestry. Conversely, maximum forest growth and a TOC gain of approximately 2 Mg ha^{-1} y^{-1} could be sustained in the future should forest thinnings be managed at a similar intensity to that implemented during the late phase of the first rotation period (Fig. 4) such as achieved by continuous selective cutting and natural regeneration (Shanin et al., 2016; Rößiger et al., 2019). Thus, afforestation depending on tree species used, soil fertility, and management practices shows great potential for carbon accumulation and anthropogenic CO_2 emissions offset. For this reason, cropland conversion is a viable option for boosting carbon sink levels and contributing to Finland’s net-zero emissions target by 2050 (IPCC, 2018a; 2018b; 2019).

Due to lack of incentives provided by agricultural policy to reduce cultivated areas across the EU within the 2020 – 2030 horizon, afforestation of cultivated land would be feasible for only a small fraction of fields (4.9 thousand ha, 0.22% of arable land) whereas extensification (18.7 thousand ha, 0.83% of arable land) is deemed more viable according to LUC planning (Table 1). Extensification is seen as more acceptable by landowners who consider it an important potential food security reserve (Peltonen-Sainio et al., 2019; Kekkonen et al., 2019). For the first decade after LUC, TOC gain from extensification would generate a significant carbon sink of 4.14 Gg $year^{-1}$ comparable to that of afforestation. Afforestation, however, would gain more importance than extensification in the long-term. Over 50 years the total benefit of afforestation in the whole of Finland would result in an estimated TOC gain of approximately 9 Gg $year^{-1}$ (8.5 Gg $year^{-1}$ by spruce or 9.3 Gg $year^{-1}$ by birch), whereas TOC gain from extensification would be just 1.7 Gg $year^{-1}$ (Fig. 5, Table S2). Beside the displacement of emissions through the land use change and carbon accumulation in the soil and tree stand, the harvested wood products (HWP) would provide additional substitution benefits of CO_2 emissions (e.g., in the energy or in the housing sector) (Myllyviita et al. 2021). Leskinen et al. (2018) estimated substitution benefits of HWP in a range between 0.7 and 5.1 Mg C due to uncertainties depending on final fate of wood, future technologies, and policy instruments.

Finland’s 2018 net national greenhouse gas emissions with LULUCF sector (emissions plus removals) of 46.3 million tonnes CO_2 eq. (Statistics Finland 2020), equivalent to 12.6 Pg $year^{-1}$ of C, would be offset by 10.7 Gg C $year^{-1}$ (0.01%) over the next 50 years should a combined 0.83% extensification and 0.22% afforestation of arable land be implemented. However, such a reduction on the national level would make only a minor contribution to meeting Finland’s net zero emission targets by 2050 (www.ym.fi/en/). This offset of C emissions could be larger if our future simulations were based not on the highest climate warming scenario RCP8.5 but rather on intermediate stabilization pathways. However, this difference between scenarios becomes larger than 1 °C only after 2050 and towards the end of the first forest rotation period, thus outside the period set for achieving the carbon neutrality target by policymakers. In the absence of natural disasters, the mean total carbon sink could be expected to increase up to 30% as simulated by the upper range of increased future forest growth. Furthermore, our estimates were premised on the current trend of afforestation (4.9 thousand ha over the next 10 years) which is relatively small compared to the 250 thousand ha of grasslands that have no evidence of use and are not undergoing natural reforestation as estimated by the National Forest Inventory in Finland (Korhonen et al., 2020). Adjusting these parameters could achieve a national offset of Finland’s net CO_2 emissions from 0.01% up to 4% which is comparable to offsetting capabilities of afforestation in Canada (Boucher et al., 2012). Due to presented time delay and relatively small annual offset of national emissions, and due to the limitations in the land area needed for ensuring food security, the afforestation cannot be considered as a major solution to climate change (Doelman et al., 2020).

4.2. Reliability of the results

Estimated SOC stocks at the end of the cultivation period agreed with both the scaled SOC observations to 1 m from a depth of 15 cm and confidence intervals (Heikkinen et al. (2013) cited by Palosuo et al. (2015)) (Fig. 2, Fig. S4). Our estimates of SOC loss rate from cropland cultivation in Southern Finland was on average 0.55 Mg ha^{-1} y^{-1} at a soil depth of 100 cm. This is similar to the 0.67 Mg ha^{-1} y^{-1} rate based on deforestation experimental sites reported by Karhu et al. (2011) (Fig. 3a) and comparable to topsoil (0–15 cm) estimates originating from Finnish national SOC inventories 0.22 Mg ha^{-1} y^{-1} (Heikkinen et al., 2013). Simulations of SOC gain after cropland extensification in Southern Finland were comparable to European projections (Smith, 2005) as well as a similar simulation study conducted in Russia (Heikkinen et al., 2014) and were consistent with known rate decreases of SOC accumulation over time (Smith et al., 2016).

The rate change in soil carbon loss/accumulation for a given climate and litter input level depends on differences between equilibrium SOC stock, present SOC stock, and soil carbon potential (Luo et al., 2016, Lal, 2016). This means that the greatest potential for SOC change at the highest rate follows a change in litter input after LUC and saturates over time. The estimated equilibrium SOC of natural forest, particularly in the South region, has been shown by other studies to be higher than simulated SOC stocks of pre-cropland forest and managed forests (Akujärvi et al., 2014, Lehtonen et al., 2016). The higher modelled equilibrium forest SOCs reported in our study were derived from assumed conditions of historical forests such as slightly larger litter inputs and colder climates. However, the simulated SOCs of cultivated land in our study taken together with upscaled SOC stocks observations (Palosuo et al., 2015) and SOC loss rates recorded at the sites of a deforestation experiment carried out in southern Finland (Karhu et al., 2011) were similar (Fig. 3).

The estimated initial SOC loss after afforestation agreed with data reported by Karhu et al. (2011), except for one site that might have been a sink, although the uncertainty of their observations was large (Fig. 4). For example, the uncertainty bounds of reported measurements just from afforestation of bare land were greater than modelled differences between two afforestation alternatives (afforestation of bare land or extensification of grassland prior to afforestation) regardless of tree species. SOC accumulation following afforestation was small (Fig. 3) and estimates showed positive or negative trends when compared to SOC change associated with cultivation (Fig. 4). This was in accord with experimental and other SOC simulations studies (Karhu et al., 2011, Hernández et al., 2017). Initial litter input was uncertain as biomass models do not exist for tree seedlings and saplings below 5 cm in diameter. Furthermore, total litter input after LUC can be affected by natural regeneration of wind dispersible perennial plants as well as woody species. However, larger carbon sink produced by afforested managed grassland would be preferable over that created by afforestation of bare fallow.

Uncertainty in projected simulations (Fig. 2) covered errors in models of biomass, litter, and climate. This could be approximately 30% when applying the Yasso07 model with biomass and litter inputs based on forest inventory measurements (Lehtonen and Heikkinen, 2015). Biomass models were predicated on historical trends of temperature and precipitation but future forest growth and forest sink in a warming climate are expected to increase by 30 % (Sievänen at el. 2014). However, growth changes based just on increased temperature and precipitation without taking into account increased risks (nutrient limitation of growth and mortality due to pathogens, insect outbreaks, wind storms, and droughts) could not be used one-sidedly in projections as the risks of climate change may outweigh the benefits.

4.3. Environmental effects on carbon sequestration potential

Modelling results assumed that SOC accumulation in mineral forest soils is predominantly dependent on litter quantity, litter quality, and climate (Tuomi et al., 2011). The soil carbon sequestration potential resulting from afforestation was thus dependent on tree species as spruce and birch differ in, for example, quantity of fine-root litter (Lehtonen et al., 2016) and chemical quality of foliage (Johansson, 1995). Afforestation by silver birch generated greater soil carbon accumulation than Norway spruce, this being mainly due to larger fine-root biomass and better growth in medium fertile soils (Repola, 2008, 2009). Mixed spruce and birch stands may acquire a larger biomass earlier in maturity than pure spruce stand (Fahlvik et al., 2011). If agricultural land to be afforested by spruce is adjacent to forest, birch as a pioneer species could regenerate naturally and result in mixed stands with enhanced soil carbon accumulation. However, older birch trees are normally removed from spruce stands to avoid the negative effect on spruce crown growth caused by whipping.

Factors other than litter and climate were accounted for in the model only by explicit parametrization with large data (Tuomi et al., 2011). These factors, e.g., decomposer microorganisms, soil fertility and soil carbon mineral association, may be locally more important for decomposition and SOC accumulation (Fernández-Martínez et al., 2014; Bradford et al., 2016). Agricultural soils are often more fertile, fine-textured and have higher clay content than forest soil (Karhu et al., 2011). Soil fertility was directly accounted for in the quantity of litter produced by dominant tree species but not in the model's litter decomposition rates. However, not including soil property as a control for SOC accumulation in the Yasso07 model leads to SOC underestimation in highly fertile soils and in soils with high clay content (Ťupek et al., 2016). Although the Yasso07 model has been widely calibrated, tested against SOC data, and applied to future scenarios (Tuomi et al., 2009; Rantakari et al., 2012; Karhu et al., 2011; Palosuo et al., 2015; Hernández et al., 2017), it requires further development with respect to improved representation of soil carbon pools, climatic effect on decomposition (such as feedback between soil properties and decomposition) as well as its applicability to organic soils. In this study, we evaluated mineral soils that compose 90% of the croplands in Finland, but additional potential can be found in organic soils (Kekkonen et al., 2019).

Our afforestation area estimates were based on a land use optimization tool that accounted for the trend that currently stands at approximately 500 ha of mineral cropland annually (Table 1). Larger scale schemes aimed at poorly performing mineral soils and of organic fields would require providing support to farmers. This could be achieved through initiatives advocating afforestation as a means to offset personal CO_2 emissions or via changes in European agricultural policy incentives. Currently, efforts to reduce cropland areas have not been implemented, since cropland maintenance is promoted even in cases where fields are not being used for food or feed production and even though they continue to be sources of CO_2 emissions. Assuming that forest growth occurs for at least 30 years and that the resulting contribution to total carbon sink will be approximately 2.0 Mg year^{-1} of C, we found that offsetting average personal CO_2 emissions in Finland of 10300 kg year^{-1} (Statistics Finland, 2020), equivalent to 2.8 Mg year^{-1} of C, would require the afforestation of 1.4 ha of cropland or grassland per capita (Fig. 4).

5. Conclusions

We demonstrated that afforestation of poorly performing cropland or extensive grassland can be an effective method for creating the carbon sink required to offset personal CO_2 emissions yet is not sufficient to achieve Finland's national net-zero emissions target by 2035 or 2050. Afforested land could in the long-term accumulate approximately 0.4 Mg ha^{-1} year^{-1}, which is 5 times more than the 0.08 Mg ha^{-1} year^{-1} SOC gained by extensification. However, the annual SOC benefits of extensification would be 1.4‰ in the first 10 years and decrease to 0.7‰ over 50 years, which is lower than the target proposed by the "4 per mil" initiative for offsetting global anthropogenic CO_2 emissions. The afforestation area estimate in our study was based on current trends. However, according to the national forest inventory (Korhonen et al., 2020) the available area of abandoned grasslands with potential for afforestation could be up to 250 000 ha. In addition to afforestation other soil carbon sequestration methodologies need to be explored e.g. mulching with stable organic residues or by adding biochar (a by-product of low-temperature wood chip combustion). Such amendments would help restore soil carbon loss incurred due to the absence of woody plant litter input during cultivation.

Tree biomass carbon sink combined with soil carbon benefit following afforestation totalled approximately 2.0 Mg ha^{-1} year^{-1}, the sequestration rate that was reached with a 30-year delay necessary for forest maturation and continued onwards. Finland's total benefit after 0.22% of arable land afforestation could be near 9 Gg C year^{-1} whereas carbon gain from extensification of 4 times a larger area would be just 1.7 Gg C year^{-1} over the same period. These soil and biomass carbon sinks have the potential for reversal should forest be converted to alternate land use, but not if the forest land use were to remain preserved.

6. Data and code availability

The input data and the R scripts of Yasso07 soil carbon model simulation reproducing the SOC analysis, output data and the figures (Fig. S4, Fig. 2 and Fig. 3) are available at https://github.com/boristupek/OPAL_LUC_C_sink_Finland. The more detailed pre-processing of the litter and climate data and post-processing of the total ecosystem carbon development can be also made available upon reasonable request from the first author.

CRediT authorship contribution statement

Boris Ťupek: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing. **Aleksi Lehtonen:** Conceptualization, Funding acquisition, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **Raisa Mäkipää:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - review & editing. **Pirjo Peltonen-Sainio:** Data curation, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **Saija Huuskonen:** Data curation, Investigation, Methodology, Validation, Visualization, Writing - review & editing. **Taru Palosuo:** Data curation, Validation, Visualization, Writing - review & editing. **Jaakko Heikkinen:** Data curation, Validation, Visualization, Writing - review & editing. **Kristiina Regina:** Conceptualization, Funding acquisition, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2021.119672.

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