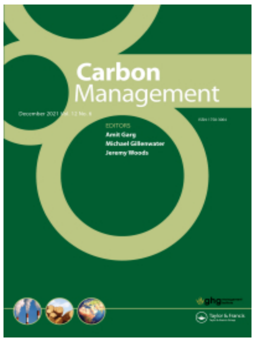

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Joel Kostensalo[a], Jari Hyväluoma[b], Lauri Jauhiainen[b], Riikka Keskinen[b], Visa Nuutinen[b], Pirjo Peltonen-Sainio[c] and Jaakko Heikkinen[b]

[a]Natural Resources Institute Finland, Joensuu, Finland; [b]Natural Resources Institute Finland, Jokioinen, Finland; [c]Natural Resources Institute Finland, Helsinki, Finland

ABSTRACT

A successful crop rotation choice is key to the profitability and sustainability of farm management and may simultaneously have an impact on soil organic carbon (SOC) content. In this study, we estimated how changes in crop rotations affected SOC balance in Finland between 2009 and 2018, using geospatial data and Bayesian modeling. The area designated for perennial-dominated and diverse cereal rotations increased over the study period. Perennial grassland rotation was found to have a positive impact on SOC balance, while rotations dominated by annual crops did not differ in their impacts on SOC content. At the national scale, changes in Finnish crop rotations resulted in an estimated annual mitigation of the loss of SOC content by 1336 Mg C year^{-1} in mineral soils and reduced the carbon dioxide emissions of organic soils by 10,475 Mg C year^{-1}. The combined effect of these two contributions is 11,811 Mg C year^{-1}, with an 80% probability interval of (−6600; 30,300) Mg C year^{-1}. While the overall impact of changes in crop rotations on SOC is relatively small, a continued change to more diverse and perennial-dominated crop rotations may have other agronomic and environmental benefits, e.g. on resilience and biodiversity.

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Crop rotations; soil organic carbon; Finland; carbon sequestration; mineral soils; organic soils

Introduction

Soil stores a significant amount of carbon as soil organic matter [1,2]. Given the enormous absolute size of this carbon stock, even relatively minor changes in soil organic carbon (SOC) content can have a significant effect on the CO_2 level of the atmosphere. It has been suggested that with proper management, soils could store significantly more carbon than presently, and carbon sequestration in soils could therefore be utilized to counteract anthropogenic greenhouse gas (GHG) emissions [3,4]. It has even been proposed that improved soil management strategies could lead to an accrual of SOC stock at a rate that would substantially compensate for the CO_2 emissions from the consumption of fossil fuels [5,6], although some other researchers regard such an objective unattainable [7–10]. An additional driving force for SOC accrual in arable topsoil is the role of SOC content in maintaining and improving important soil physical functions [11,12]. However, despite the calls to increase SOC stocks, several European studies indicate that SOC content is systematically decreasing in agricultural soils [13–18].

In general, soil management practices may significantly influence soil carbon sequestration [6,19], and diverse crop rotations, including perennial grasses, promote SOC accrual [18]. Long-term modeling of SOC dynamics has indicated that the inclusion of grasslands within crop rotation and extending their duration are effective means of increasing SOC stocks compared to many other management practices [20,21]. Grassland establishment leads to high inputs of organic matter and reduces soil disturbance, which slows the degradation of organic matter. In young grasslands, this leads to the accumulation of SOC, which can persist over long periods [22]. However, tillage of grasslands or even a single plowing event in a grass-to-grass renovation have been found to significantly reduce carbon stocks [23,24]. In crop rotations including perennial grasslands, these counteracting processes lead to a new SOC equilibrium, and the increase in the proportion of

CONTACT Joel Kostensalo joel.kostensalo@luke.fi Natural Resources Institute Finland, Yliopistokatu 6B, FI-80100 Joensuu, Finland

temporary grasslands in the rotation may have an incremental effect on the SOC accrual [25].

After a change in soil management, SOC stocks evolve toward a new steady state, which may mean either a higher or a lower SOC content, depending on how the management practices are altered. Typically, the time needed to reach a new equilibrium is long, which is why it can be difficult to determine whether a soil has reached a stable level of SOC at a given time [26]. After deploying new management practices, the SOC change typically occurs on a decadal time scale [27] but may in some cases take more than a century [22,28]. To further complicate the issue, SOC loss related to the conversion of cropland to grassland may happen on a shorter time scale than the restoration of SOC in the reverse process [29]. It is thus likely that most soils are in a transient state between two equilibria, and their SOC content does not fully reflect the SOC stock corresponding to the current SOC inputs and degradation.

Changes in SOC content following the deployment of novel soil management practices have been determined in long-term experiments [27,30–32]. Oscillations in SOC have been observed during crop rotation phases where certain phases accumulate, and others diminish, SOC [33]. It has also been found that equilibrium SOC values may change over time due to the continuously changing climate [26].

In Finnish arable soils, the SOC content has been found to decrease almost linearly in the last four decades [16]. Changes in SOC stock have been associated with land-use history, management practices, and climate change [18]. This study aims to explore the recent changes in crop rotations in Finland and to quantify their impact on the nationwide SOC content by combining several geospatial datasets with the results of the national soil monitoring network. We aim to quantify the overall effect of the ongoing short-term changes in crop rotations on SOC balance and to put this into perspective by comparing it with Finland's total annual GHG emissions.

Materials and methods

The cultivated areas for each crop rotation in Finland were calculated based on two geospatial datasets: (1) the database of management and cultivated crop plants by the Finnish Food Authority; and (2) the Finnish Soil Database [34]. The Soil Database was used to identify whether the soil type of a field parcel should be classified as a mineral or an organic soil. Changes in SOC content in mineral soils were estimated by combining the results of the national soil monitoring network with the European observational (E-OBS) climate data grid [35] and the database of the Finnish Food Authority. Emissions of organic soils were estimated by using default emissions factors by the Intergovernmental panel on climate change (IPCC) [36]. A flowchart of the analysis is presented in Figure 1.

National soil monitoring network

Finland's arable soil monitoring network was established in 1974, and plots were resampled in 1987, 1998, 2009, and 2018. However, coordinates

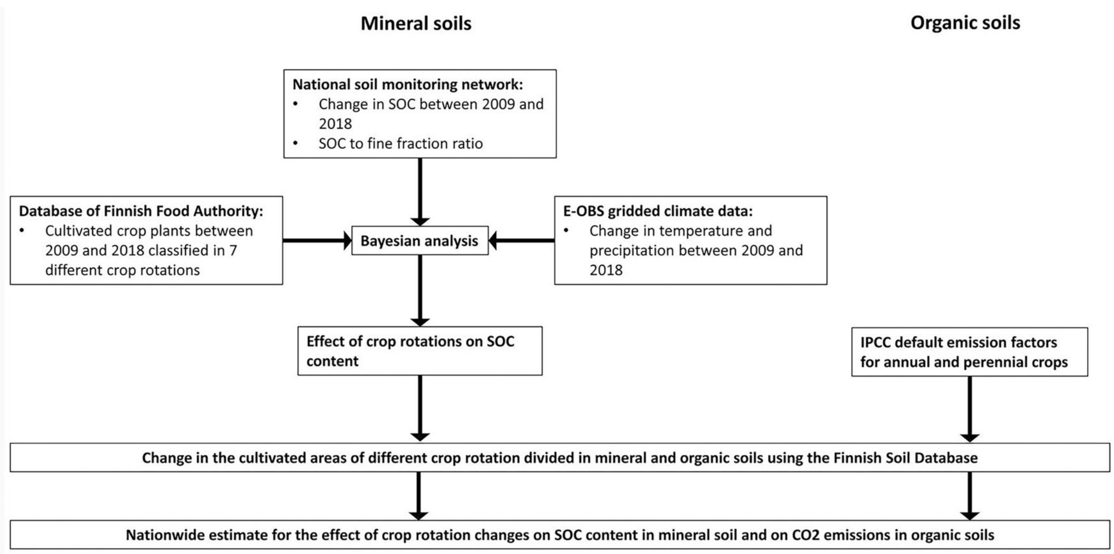

Figure 1. Schematic illustration of the workflow and the geospatial datasets used in the study. Notes: SOC refers to soil organic carbon, E-OBS is the European observational climate grid, and IPCC is the Intergovernmental Panel on Climate Change.

of all sampling plots have been determined using Global positioning system (GPS) from 2009 onward, resulting in much less scatter in the data due to the inaccuracy of the sampling plot location compared with earlier sampling campaigns (see [16,18]). This study was therefore based on the SOC content of the mineral soil samples collected in 2009 and 2018. In 2018, the soil monitoring network had a total of 620 sampling plots. For this study, the number of sampling plots was 323, as organic soils (as defined by organic matter > 20%), plots that had not been sampled in both 2009 and 2018, and plots for which crop rotation could not be classified were omitted. Figure 2 presents the location of the plots.

Soil samples were collected from 10 m × 10 m areas using a soil corer with a diameter of 2 cm. Samples were taken from the topmost 15 cm soil layer. The samples were air-dried, ground, and passed through a 2 mm sieve. The soil organic C content of the samples was determined by the dry combustion method using a LECO CN-2000 analyzer (LECO). Soil texture was determined using the sieve-pipette method [37].

Classification of crop rotations

The crop rotations were classified as in earlier studies [38]. The classification is based on the occurrence of different crop species in a five-year rotation. Rotations were classified for two periods: from 2009 to 2013, and from 2014 to 2018, based on the database of the Finnish Food Authority. The above periods were selected because they coincide with the sampling campaigns of the national soil monitoring network.

The crop rotations were classified as: (1) cereal species monoculture rotation, in which the same

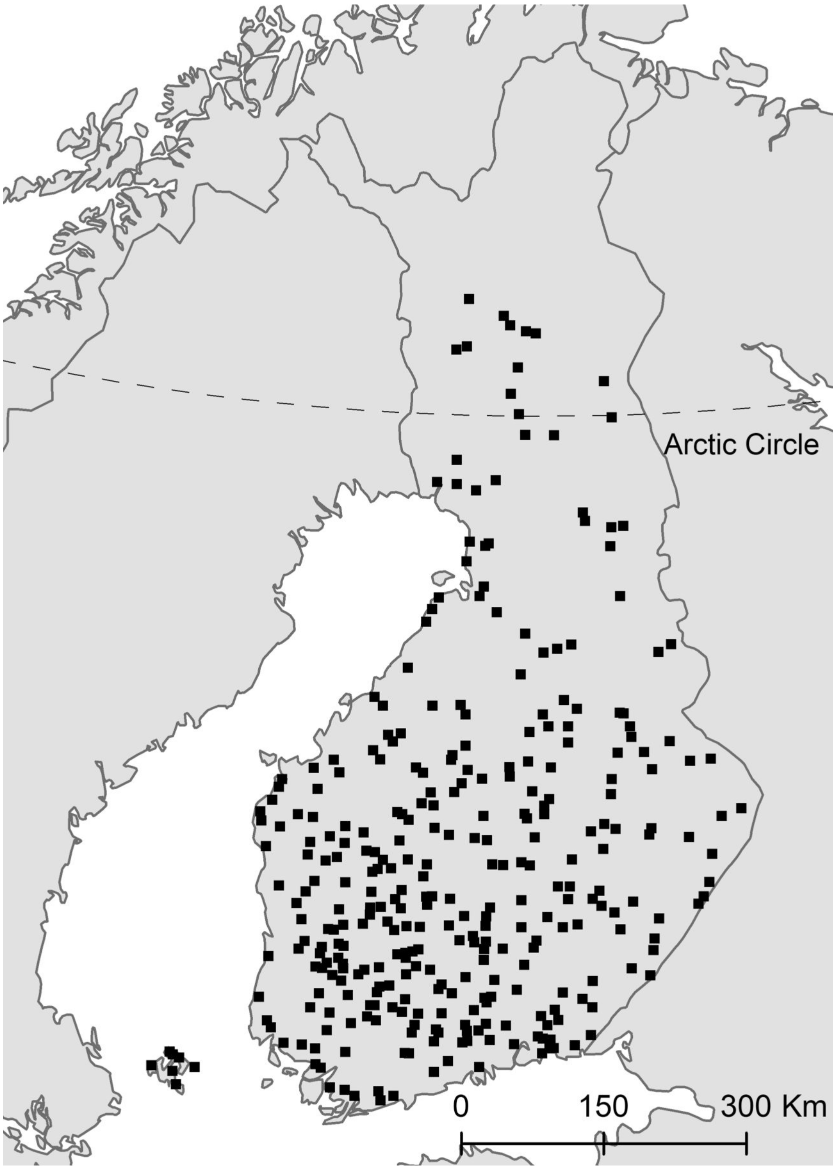

Figure 2. Location of parcel-scale sampling plots of the Finnish national soil monitoring network utilized in this study ($n = 323$).

cereal species was grown in a field for at least four years (usually barley (*Hordeum vulgare* L.) or oats (*Avena sativa* L.) only); (2) cereal monoculture rotation, in which two or more cereal species were included in the rotation (often spring or winter wheat (*Triticum aestivum* L.) and winter rye (*Secale cereale* L.)); (3) a rotation with a break-crop, in which a crop species other than cereals (often a grain legume or rapeseed) appeared once in the cereal-dominated crop rotation; (4) diverse crop rotation, in which spring and winter cereals appeared for one or two years, and at least two other crops were included in the rotation; (5) perennial grassland rotation, in which nonpermanent grass was produced for at least three years (the fields used for grazing and ones with harvested hay or silage could not be differentiated); and (6) green fallow rotation, in which green fallow, nature-managed fields, or diverse game fields were grown for at least three years. Fields in the green fallow rotation encompass a range of extensively managed fields sown with perennial or annual grasses, meadow plants or forage plants with the purpose of increasing biodiversity and providing feed and shelter for wild game animals (moose, dear, fowl). These fields may also be used for grazing and need to be mown to prevent growth of trees and bushes.

Farmers often divide field parcels into several agricultural parcels in which different crop species are grown. Locations of agricultural parcels cannot be positioned exactly within the field parcels, and only those field parcels for which the largest agricultural parcel covered ≥70% of the total field parcel area were therefore included in this study.

Effect of crop rotation on SOC

For mineral soils, the statistical analysis is based on a Bayesian framework [18]. The model captures the high and non-trivial spatial variation in SOC content with a mixing model where the changes in SOC levels follow a mix of two normal distributions, one narrower and one wider. Details, justifications, model performance, and extensive discussion of the model and the necessity of each part of it were reported earlier [18]. For this study, the main interest is the effect of crop rotations. In addition, the model was controlled for changes in precipitation and temperature, as well as the organic-carbon-to-fine-soil ratio, which also affects the SOC levels.

The basic idea behind the model is that after controlling for climate, management practices, a random effect associated with the measurement group, and soil properties, the unexplained residual variation in SOC change follows a distribution, which is a mix of two normal distributions (instead of the standard one normal distribution in a basic linear model). The two normal distributions have the same mean, but one is wide, and one is narrow. When the two measurements, which were carried out almost a decade apart, have been done very close to each other, the variation is relatively small, and the observation is from the narrow distribution. However, if the measurements differ in location even by some meters, the variation can be much larger due to the huge spatial variation of SOC, and thus the observation is from the wider distribution. As we cannot know for which plots the re-location has been successful (as it depends on the local variation in SOC), each measurement has some non-zero probability of belonging to either one of the distributions.

The formulation of the model may appear somewhat complicated, but regarding the research questions of this study, the majority of the parameters are nuisance parameters, i.e. parameters which are not of interest, but which are needed to properly capture the structure of the data. Formally, the model can be written as

$$
\begin{aligned}
\Delta\mathrm{SOC}_i|\mu_i,\sigma_i &\sim N(\mu_i,\ \sigma_i^2),\\
\mu_i = \nu + \sum\nolimits_{r\in\mathrm{Rotations}} \beta_{rot,r} Rot_{r,i} &+ \beta_{\mathrm{change\ P}} P_i \\
&+ \beta_{\mathrm{change\ T}} T_i + \beta_{fine} \log(\mathrm{Org\ C/fine\ soil})_i \\
&+ u_{\mathrm{Group}(i)},\\
\sigma_i|\pi &\sim \mathrm{Cat}(\sigma_1,\ \sigma_1+\sigma_2;\ \pi,\ 1-\pi)\\
u_{\mathrm{Group}(i)} &\sim N\left(0,\ \sigma^2_{\mathrm{Group}}\right),
\end{aligned}
$$

where for plot i : $\Delta\mathrm{SOC}_i$ is the change in SOC, ν is an intercept term corresponding to cereal species monoculture rotation with no changes in temperature or precipitation, and an organic-carbon-to-fine-soil-ratio of 1, $Rot_{r,i}$ is an indicator variable which has the value of 1 if the plot i is farmed using the rotation r and 0 otherwise. P_i and T_i denote changes in total rainfall and annual average temperature, respectively. $(\mathrm{Org\ C/fine\ soil})_i$ is the organic-carbon-to-fine-soil-ratio, βs are the regression coefficients to be fitted, $u_{\mathrm{Group}(i)}$ is a measurement-group-specific random effect, and the σs form the covariance structure, with σ_1 being the standard deviation of the narrow distribution, $\sigma_1+\sigma_2$ that of the wide distribution, and $\sigma_{\mathrm{Group(i)}}$ that of the random effect, with π being the probability that the observation is from the narrow distribution, and $1-\pi$ the probability that the observation is from the wide distribution. N

refers to a normal distribution and Cat to a categorical distribution. We use uninformative priors and sufficient efficient sample sizes as specified by Heikkinen et al. [18]. The fit was done using JAGS software (Just Another Gibbs Sampler [39]), and the statistical software R [40].

For the purposes of this study, we are interested in the parameters β_r, which describe the difference in annual SOC sequestration/loss between a given rotation *r* and the cereal species monoculture rotation. With the Bayesian approach, by specifying a model and fitting it with our data we get a probability distribution $P(\beta_r)$, known as a posterior distribution, from which we can infer a likely value for the parameter β_r and its probability distribution. A natural point estimate for the parameter is the expected value of the distribution $E(P(\beta_r))$. For hypothesis testing, the probabilities $P(\beta_r > 0)$ and $P(\beta_r < 0)$ are analogous to frequentist one-sided *p*-values, as they describe the probability that the parameter has a given sign. Probabilities above 95% are considered here as solid evidence of a difference between the rotations. A range of likely values is described by a probability interval (i.e. the posterior interval or Bayes interval) which is analogous to the frequentist confidence interval, but the interpretation is more straightforward, as it directly produces a probability that the value of the parameter is contained within the interval. In Bayesian statistics, the traditional choice is to use an 80% probability interval (80% PI), which we also adopt for this work. For further information about Bayesian statistical analysis, see Gelman et al. [41].

Emissions of organic soils were estimated using the default emissions factors from the IPCC [36], which are 7900 kg C ha^{-1} $year^{-1}$ (95% confidence intervals, ranging from 6500 to 9400 kg C ha^{-1} $year^{-1}$) for annual crops and 5700 kg C ha^{-1} $year^{-1}$ (2900–8600 kg C ha^{-1} $year^{-1}$) for perennial grasses. Organic soils were identified using the Finnish Soil Database [34] by extracting the soil type based on the coordinates of the center point of the field parcel.

Results

Changes in crop rotation area

In mineral soils, the cultivated area of cereal species monoculture and rotation with break-crops decreased between 2009–2013 and 2014–2018 (Figure 3a). A decrease by 52,800 ha in cereal species monoculture and 47,100 ha in rotation with break-crops was observed. On the other hand, the greatest increase in cultivated area was found for cereal monoculture rotation (53,100 ha), followed by perennial grassland (28,400 ha) and green fallow rotation (22,100 ha). The cultivation area designated for diverse rotations was found to have increased by 10,000 ha. In mineral soils, the crop rotation class changed in 52% of the cultivated area between the periods 2009–2013 and 2014–2018.

In organic soils, the changes were qualitatively similar to those in mineral soils, with the area occupied by cereal monoculture, diverse rotation, green fallow rotation, and perennial grass rotation increasing, while the total area for other rotations decreased (Figure 3b). However, in organic soils, the greatest area increases were those of green fallow and perennial grassland rotations, with

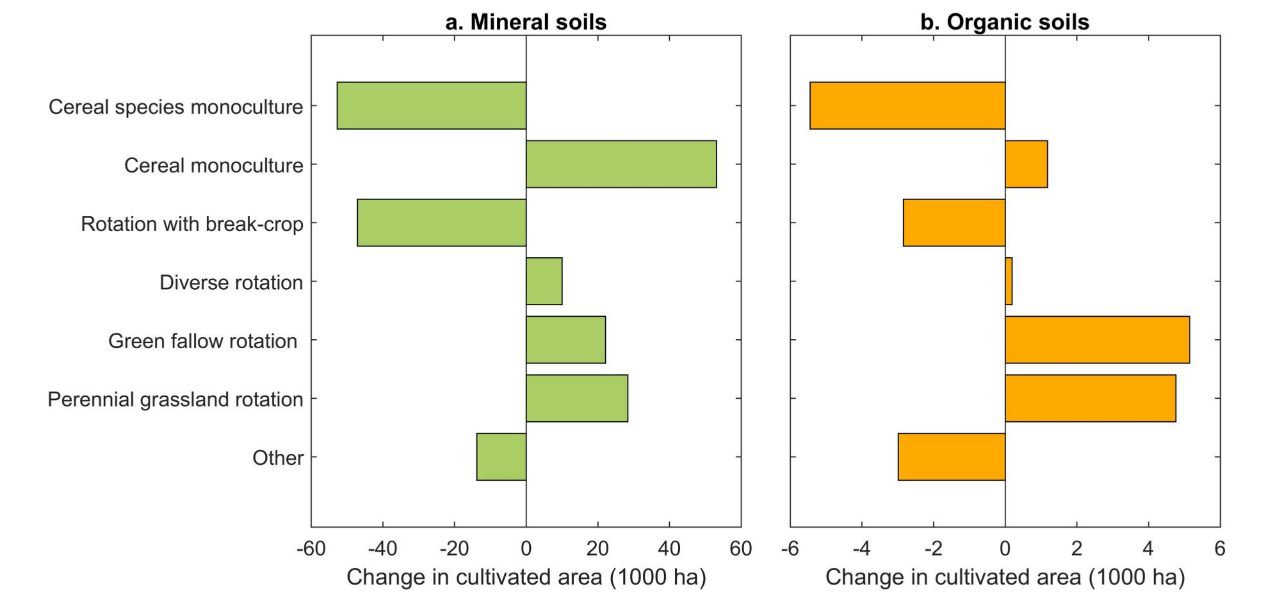

Figure 3. Changes in cultivated area under different crop rotations in the entire country of Finland between 2009–2013 and 2014–2018 in hectares (ha) for (a) mineral and (b) organic soils.

increases by 5100 and 4800 ha, respectively. According to the present data, the share of organic soils is 10.6% of the total agricultural area. In organic soils, the proportion of fields where the rotation changed was 45% between the classification periods 2009–2013 and 2014–2018.

Effect on SOC content

Mineral soils

Table 1 presents the results from the Bayesian model fit for mineral soils. Perennial grassland rotation stood out as the most beneficial cropping system with respect to SOC accumulation between 2009 and 2018. As indicated by 80% PIs, the perennial grassland rotation has a clear indication of deviating from cereal species monoculture with respect to its effect on SOC concentration. For green fallow rotation the point estimate was also positive, but the size of the effect was smaller – only about 10% of that of the perennial grass rotation – and the 80% PI includes both negative and positive values. The point estimates for monotonous cereal species sequencing, rotation with break-crop, and diverse rotation are negative, meaning that based on this dataset, it is possible that these rotations are counterproductive with respect to SOC accrual compared to cereal species monoculture.

Other variables included in the model show that changes in SOC concentration were strongly associated with the initial SOC-to-fine-fraction ratio, indicating that soils with a large amount of SOC or coarse texture tend to lose more carbon than soils with a higher amount of fine fraction particles relative to the SOC concentration. The results also indicate that an increase in both temperature (May–September) and precipitation led to SOC losses. These findings are in line with the earlier study [18] but are beyond the scope of this study, as the variables were included in the analysis only to control for effects unrelated to crop rotations.

The overall national-level impact of crop rotation changes was calculated by combining the estimated changes in SOC content per hectare with the cultivated areas of each conversion class combination (Table 2). By summing up the effects of each converted crop rotation class combination, the nationwide accumulation of SOC can be estimated to be approximately 1336 Mg C year^{-1} in mineral soils. However, the 80% PI is extremely wide, varying from an order of magnitude higher SOC loss to an order of magnitude higher SOC accumulation.

Organic soils

The area of perennial grassland rotation in organic soils increased by 4800 ha between the classification periods of 2009–2013 and 2014–2018 (Figure 3). Using the IPCC default emission factors, the increase in area of perennial grassland rotation corresponds to an annual emissions reduction of approximately 10,475 Mg, with the 80% PI varying from an emissions reduction of 476 Mg to 20,476 Mg. Regionally, the emissions of organic soils decreased in the regions where perennial-dominated crop rotations increased in area (Figure 4). As the uncertainties related to mineral and organic soils can reasonably be assumed to be independent given that the numbers originate in different models and datasets, the combined effect of mineral and organic soils on SOC is 11,811 Mg C year^{-1}, with an 80% PI of (−6600; 30,300) Mg C year^{-1}.

Table 1. Effect of crop rotations, climate change, and SOC-to-fine-fraction ratio on soil organic carbon (SOC) content change ($E(\theta y)$) using E-OBS climate data, 80% (equally tailed) probability interval, and probability of positive effect ($P(\theta > 0)$).

		Effect on SOC concentration $E(\theta y)$ (g kg^{-1} year^{-1})	80% PI (g kg^{-1} year^{-1})	Probability $P(\theta > 0)$
Crop rotation (vs. Cereal species monoculture)	β_r			
Cereal monoculture		−0.084	(−0.202, 0.036)	.18
Rotation with break-crop		−0.051	(−0.177, 0.076)	.30
Diverse rotation		−0.186	(−0.459, 0.089)	.19
Green fallow rotation		0.014	(−0.129, 0.160)	.55
Perennial grassland rotation		0.136	(0.032, 0.240)	.95
Other		−0.043	(−0.168, 0.081)	.33
SOC to fine fraction	$\beta_{\log(OrgC/fine)}$	−0.189	(−0.236, −0.143)	<.0001
Climate change				
1 mm increase in precipitation sum	$\beta_{change\ P}$	−0.0030	(−0.0061, −0.0003)	.078
1 °C increase in temperature	$\beta_{change\ T}$	−0.541	(−0.962, −0.129)	.049
Other parameters				
Constant	μ	0.177	(−0.042, 0.397)	0.85
Narrow distribution fraction	π	0.79	(0.72, 0.85)	1
Wide distribution fraction	$1-\pi$	0.21	(0.15, 0.28)	1
SD of narrow distribution	σ_1	0.289	(0.252, 0.328)	1
SD of wide distribution	σ_3	1.311	(1.111, 1.544)	1
Measurement group effect	σ_{group}	0.083	(0.028, 0.142)	1

Here, θ denotes an arbitrary parameter of interest.

Table 2. Cultivated area of each crop rotation class combination in 2009–2013 and 2014–2018, corresponding emission factors (kg C ha year^{-1}), and overall effect on soil organic carbon (SOC) stock (Mg C year^{-1}). The effects (EF) have been given per hectare (ha).

Rotation 2009–2013	Rotation 2014–2018	Area (ha)	EF (kg C ha^{-1} year^{-1})	Effect on SOC (Mg C year^{-1})
Cereal monoculture	Cereal monoculture	75,684	0	0
	Cereal species monoculture	38,567	133	5132
	Diverse rotation	3375	−162	−545
	Green fallow rotation	4513	155	701
	Other	21,740	65	1412
	Perennial grassland rotation	15,529	348	5412
	Rotation with break-crop	42,434	52	2218
Cereal species monoculture	Cereal monoculture	62,666	−133	−8338
	Cereal species monoculture	107,993	0	0
	Diverse rotation	2329	−295	−686
	Green fallow rotation	8361	22	185
	Other	31,412	−68	−2140
	Perennial grassland rotation	27,880	215	6006
	Rotation with break-crop	48,597	−81	−3926
Diverse rotation	Cereal monoculture	4283	162	692
	Cereal species monoculture	1237	295	364
	Diverse rotation	6162	0	0
	Green fallow rotation	1368	317	433
	Other	7965	227	1804
	Perennial grassland rotation	6111	510	3117
	Rotation with break-crop	7316	214	1565
Green fallow rotation	Cereal monoculture	3544	−155	−550
	Cereal species monoculture	4001	−22	−89
	Diverse rotation	1681	−317	−533
	Green fallow rotation	127,904	0	0
	Other	18,558	−90	−1676
	Perennial grassland rotation	35,403	193	6842
	Rotation with break-crop	8380	−103	−863
Other	Cereal monoculture	25,837	−65	−1678
	Cereal species monoculture	23,263	68	1584
	Diverse rotation	12,090	−227	−2739
	Green fallow rotation	22,345	90	2018
	Other	97,367	0	0
	Perennial grassland rotation	92,329	284	26,179
	Rotation with break-crop	48,485	−13	−614
Perennial grassland rotation	Cereal monoculture	11,072	−348	−3859
	Cereal species monoculture	14,484	−215	−3120
	Diverse rotation	6238	−510	−3182
	Green fallow rotation	46,469	−193	−8980
	Other	79,977	−284	−22,677
	Perennial grassland rotation	450,767	0	0
	Rotation with break-crop	30,540	−296	−9046
Rotation with break-crop	Cereal monoculture	71,875	−52	−3757
	Cereal species monoculture	46,896	81	3789
	Diverse rotation	12,573	−214	−2689
	Green fallow rotation	10,662	103	1098
	Other	50,887	13	645
	Perennial grassland rotation	39,928	296	11,827
	Rotation with break-crop	112,745	0	0
	Total	2,031,822		1336 (−14,000, 17,000)

Emission factors have been calculated as $(E_{2014-2018} - E_{2009-2013})/34.09 \times 54$, where 34.09 g kg^{-1} is the average SOC content in 2009, 54 t C ha^{-1} is the average nationwide SOC stock in 0–15 cm soil layer [16], and E is the change in SOC concentration as given in Table 1 ($E(\theta y)$). The 80% probability interval for the overall nationwide effect is given in parentheses.

Discussion

The diversification of agricultural land use has been identified [42] as one of the key measures for improving the sustainability and resilience of agriculture. In Finland, cereal species monocultural rotations (usually either barley or oats) have given way to more diverse cereal-dominated rotations and to some extent to diverse rotations. On the other hand, the area designated for a single break-crop during a five-year rotation has been reduced, which is probably attributable to a reduction in the cultivation of turnip (*Brassica rapa* L.) driven by increased uncertainties and yield losses experienced by farmers [43,44]. Changes in land use to higher diversity in Finland [45] have primarily been driven by systematic increases in farm size, the warming of the climate, and the opening of domestic markets for diversifying special crops [38,45,46]. On the other hand, agricultural policies have increasingly pressed for a transition to the use of environmental grasslands (i.e. green fallow rotations, Figure 2), though this has taken place in parcels with a low production capacity and structural, functional, and logistic weaknesses [47].

Among the six crop rotations considered, perennial grassland rotation, which was defined as three or more grass years in a five-year period, was discerned as the most efficient for SOC sequestration. The conversion of cropland to grassland is known

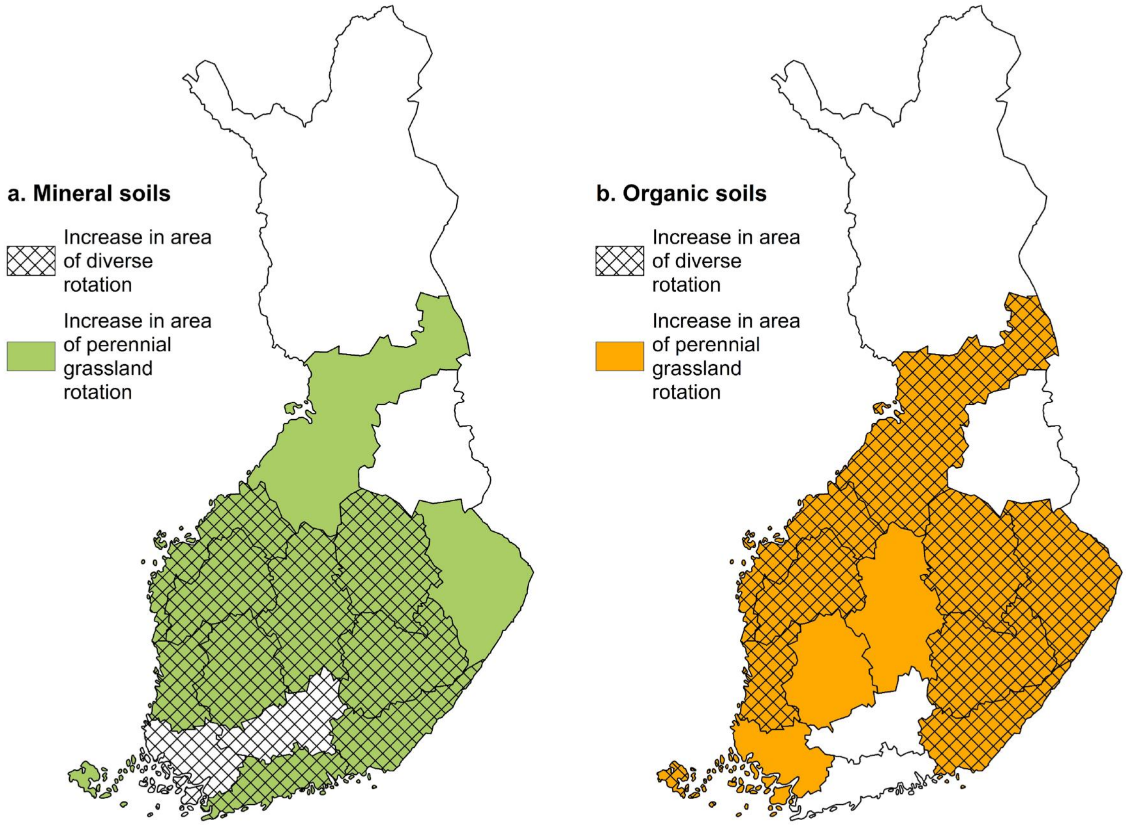

Figure 4. Changes in cultivated area under different crop rotations in specific regions of Finland between 2009–2013 and 2014–2018 in (a) mineral and (b) organic soils.

to induce SOC accumulation [28,48]. Temporary grass cultivation, i.e. rotational leys, has also been identified as an option for soil carbon management, though potentially not as efficient as the use of grasslands [49,50]. The tendency of perennial vegetation to accumulate SOC is attributed to high root-derived C input, which is more persistent in soils than carbon originating in residues of aboveground biomass [51–53]. In addition, a reduction in the frequency and intensity of disturbance through tillage in rotations containing temporary leys contributes to enhancing SOC storage [54]. The observed rates of gains (or, in some cases, losses) of SOC in grasslands vary depending on soil and environmental conditions (e.g. soil C sink capacity, the age of the ley, temperature, and precipitation) and management practices [55]. Improvements in management, such as the fertilization and sowing of new plant varieties, tend to increase SOC [56,57]. Consequently, in the current data, extensive management may at least partly explain the lack of a positive effect of the green fallow rotation, including nature-managed fields, on SOC content change. Furthermore, in this crop rotation class, fields of inherently low biomass production potential are known to be common [47,58].

An increase in the diversity of plant species within annual rotations did not promote SOC buildup or maintenance according to the current data. Similar results are common in other published crop-rotational studies [59]. However, in a previous study using a different classification for the rotations using Finnish data [18], diverse cropping systems (Shannon index $>$ 0.8) exhibited a positive SOC effect compared with annual less diverse (Shannon index $<$ 0.8) systems. This was thought to be potentially associated with an increased C input, as rotation phases with perennials were also possibly included. Another reason suggested was changes in the chemical composition of plant residues favoring SOC accumulation, changes in soil microbial community, or cultivation operations associated with the diverse rotations [59–61]. In this study, we identified crop rotations based on the five preceding years for both study periods, which may be too short a period to record any large-scale impacts on SOC, even though many diversifying crops cause immediate yield benefits for the following crops in rotation. This was evident according to the large-scale studies on farmers' fields that used satellite data to identify changes in biomass production capacities depending on pre- and following crop combinations used in crop sequencing [62]. The apparent discrepancy between the two studies may stem from their difference in the definition of perenniality. Moreover, the higher number of rotational classes in the present study decreases the number of observations per class and the statistical power of the comparisons.

Based on European agroecosystem modeling, an annual SOC increase of 400–800 kg C $ha^{-1} year^{-1}$ was found after the conversion of arable land to grassland [20]. In turn, a review of 115 studies from 17 different countries [57] showed a corresponding organic carbon increase rate of 540 kg C $ha^{-1} year^{-1}$. Another study [50] reported a SOC increase rate of 490 kg C $ha^{-1} year^{-1}$ based on a large French soil database [63]. These values are in line with the results of the present study, showing that a change from annual to perennial grassland rotation leads to SOC restoration at a rate of 193–510 kg C $ha^{-1} year^{-1}$, depending on the preceding annual rotation. However, our study showed that changes in SOC content depend greatly on the initial SOC-to-fine-fraction ratio. Thus, even though conversion from annual to grassland rotation has a beneficial impact on SOC balance, it does not necessarily result in SOC sequestration (i.e. an absolute increase in SOC content). Soils with a high level of SOC especially can lose carbon despite the cultivation of perennial grasses, but the rate of decrease is lower than in the case of annual rotations.

According to the national GHG inventory, the total emissions in Finland without the land use, land-use change, and forestry sector were 47.8 Mt CO_2 equivalent in 2020. The estimated climatic impact of the crop rotation changes in mineral and organic soils amount to 11,811 Mg C $year^{-1}$ (80% PI (−6600; 30,300) Mg C $year^{-1}$), corresponding to approximately 0.1% of total GHG emissions in Finland, with an 80% PI of (−0.05%, +0.23%). In the national GHG inventory, the CO_2 emission from cultivated soils has been reported to be 7.7 Mt CO_2 equivalent, of which 6.6 and 1.1 Mt results from organic and mineral soils, respectively. In comparison, the contribution of crop rotation changes is about 0.6%. Despite the fact that we had a decade-long high-quality data set, and used state-of-the-art modeling, the uncertainties regarding the effects of individual crop rotations are still large. These uncertainties should be carefully considered when making strategic decisions regarding climate and environmental policy. In particular, basing policy on point estimates from individual studies should be discouraged, and a sufficiently large range of probable values (e.g. an 80% PI from a Bayesian analysis, or the widely used 95% confidence interval from a frequentist analysis) should be considered in the decision-making process. On the other hand, methodological developments are needed to improve the accuracy of the estimates, which would make the decision-making process more straightforward.

The present study focused only on the effect of crop rotations on SOC balance. The study did not consider the climatic impact of possible changes in dietary or livestock feeding, which are closely associated with the choice of cultivated crop plants. Quantification of overall climatic impact would require comprehensive life-cycle assessment, including e.g. emissions of ruminants, transportations, and food processing. Furthermore, it should be noted that changes in crop rotation are only one possible mitigation measure and, particularly in organic soils, raising the water table level (controlled subsurface drainage, paludiculture, or peatland restoration) has proved to be a far more efficient way to reduce the emissions [36,64].

Despite the rather limited contribution of crop-rotation-induced changes on SOC and, further, on national C balance, the diversification of cropping systems may generate many substantial agronomic and environmental benefits, e.g. improved resilience in variable weather conditions, increased biodiversity, higher yields, improved soil water holding capacity, a reduction in pests and diseases, and enhanced water quality [65]. A crop-rotation-induced boost in belowground microbial diversity and activity would support soil functioning by enhancing nutrient cycling and strengthening soil structure formation and structural stability [66]. Furthermore, creating spatial crop diversity via versatile temporal rotations serves to promote aboveground arthropod diversity and density, thus supporting ecosystem resilience [67]. As with water quality, crop rotation diversification can help in reducing nutrient leaching and soil erosion [68], and diverse crop rotations have been shown to reduce nitrogen leaching [69]. Regarding soil erosion, for fixed SOC content, the inclusion of grass in crop rotation has been observed to have only a minor effect on soil aggregate stability compared with cereal monoculture [69]. However, as SOC content has a positive effect on aggregate stability, crop rotations can have a positive influence through an increased SOC level [70].

Conclusions

During the last decade, increased farm size, the warming of the climate, and increased demand for special crops has resulted in a diversification of crop rotations and the adoption of perennial-dominated arable systems in Finland. An increase in the cultivation area designated for perennial grasses was found to have a positive climatic impact through the accumulation of SOC into cultivated mineral soils, and by decreasing the emissions of organic soils. However, a nationwide estimate of the effect of crop rotation on SOC balance proved to be highly uncertain in both mineral and organic soils, drawing attention to the need for methodological development to assess the national-scale climatic impacts. Compared with the total GHG emissions at the national level, the climatic impacts of changes in crop rotations were ultimately relatively small, accounting for approximately 0.1% (80% PI (−0.05%, +0.23%)) of total Finnish GHG emissions. Considering that the large-scale changes in crop rotations which have occurred nationwide have had at most a minute impact on the climate, policy measures aimed solely at increasing carbon in the soil do not appear to be very effective. Instead of large-scale policies focused on soil carbon alone, policies that facilitate targeted site-specific measures with multiple simultaneous goals, including soil productivity, biodiversity, and water body impacts in addition to soil carbon sequestration, might be more justifiable.

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The authors report that there are no competing interests to declare.

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ORCID

Joel Kostensalo http://orcid.org/0000-0001-9883-1256
Jari Hyväluoma http://orcid.org/0000-0003-1113-439X
Lauri Jauhiainen http://orcid.org/0000-0003-2073-1057
Riikka Keskinen http://orcid.org/0000-0003-4025-637X
Visa Nuutinen http://orcid.org/0000-0002-8991-0830
Pirjo Peltonen-Sainio http://orcid.org/0000-0002-1083-2201
Jaakko Heikkinen http://orcid.org/0000-0002-6837-1057

Data availability statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions. The official register of cropping system and farm type used in the sampling site classification can be requested from the Finnish Food Authority: https://www.ruokavirasto.fi/tietoameista/avointieto/tiedonluovutukset.

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