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Carbon budget of Finnish croplands — Effects of land use change from natural forest to cropland

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ABSTRACT

The pool of soil organic carbon (SOC) in Finnish croplands has declined during recent decades according to nation-wide soil inventories, but reasons for this trend remain unclear. We studied the possible reasons using an approach based on the Yasso07 soil carbon model. We evaluated also the suitability of this approach for estimating the pool and changes of SOC in boreal croplands at the regional scale. The simulated SOC pool declined in each of the four study regions we divided the country into over the entire study period from 1900 to 2009. During the last 35 years, the mean estimate of the decrease rate varied from 0.29 to 0.36 Mg ha^{-1} year^{-1} among the regions. The mean estimate of the SOC pool in the croplands varied from 92 to 124 Mg ha^{-1} at the end of the study period. In a sensitivity analysis, the estimates of the decrease rate slowed down by 25% or accelerated by 38% at most, whereas the pool estimates increased or decreased by 18% at most. According to our simulations and the sensitivity analysis, the SOC pool declined because croplands produced less litter than pre-cropland forests and this agricultural litter decomposed more rapidly. On the other hand, climate warming has not been a significant reason for the decline yet. Increasing carbon input to the cropland soil by applying organic manure and avoiding bare fallow are means to slow down the loss of SOC. The simulated estimates were similar to measurement-based ones available for comparison. We concluded that our approach was suitable for studying the reasons for the declining trend of SOC and the major uncertainties were caused by inexact input values.

1. Introduction

Croplands can act as either sources or sinks of atmospheric carbon depending on environmental conditions and agricultural management practices (Lal, 2004). There is a growing concern about the negative effects of climate warming on the balance of soil organic carbon (SOC) in the croplands (Obersteiner et al., 2010). It is uncertain how land use changes and management practices will affect the SOC pools of croplands under changing climate. Agricultural management, such as selection of crops, crop rotation, fertilization and harvest intensity, is known to affect the carbon sink potential of the croplands because it determines the quantity and the composition of organic matter entering the soil (Paustian et al., 1997).

In croplands, like in all terrestrial ecosystems, the pool of SOC and changes in this pool over time are determined by the balance between carbon input as plant residues and organic amendments, and output resulting from decomposition, erosion and leaching. Previous land use, agricultural management and climatic conditions all affect the cycle of SOC (Lal, 2004). A characteristic feature of croplands is that a considerable share, often 40 to 60%, of the annual net primary production (NPP) is harvested, which reduces the fraction ending up in soil as a dead organic matter (Hay, 1995). This is seen as a major reason for declining SOC pools observed in cropland soils (Leifeld, 2013).

Changes in the SOC pool of croplands can be quantified using repeated SOC inventories or modeling at regional or national scales. In Finland, the pool and changes of cropland SOC were recently estimated based on successive soil inventories between 1974 and 2009 (Heikkinen et al., 2013). According to these inventories, the SOC pool decreased at an average rate of 0.22 Mg ha^{-1} year^{-1} during this period. The authors could not explain reasons for this trend based on the soil inventories alone, and they suggested to study them using simulation models. Such models have been used elsewhere in Europe earlier (e.g. Gervois et al., 2008; Smith et al., 2007). These studies have revealed that changes in agricultural management, such as increased harvest intensity, a shift towards mineral fertilization and cultivation of annual crops, have been the main reasons for decreasing trends in the SOC pools of European croplands.

In this study, we used the Yasso07 soil carbon model (Tuomi et al., 2009, 2011a, 2011b) to analyze reasons for the decrease in the SOC

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pool of Finnish croplands. This model is already used to estimate the carbon budget of forest soil in the national greenhouse gas inventory of Finland (NIR, 2012). The model and its predecessor Yasso (Liski et al., 2005) have also been applied in various other studies to estimate, for example, the effects of climate change (Thum et al., 2011), land-use change (Karhu et al., 2011; Lu et al., 2013), forest management (Johnson et al., 2010) and bioenergy on the SOC pool (Liski et al., 2013; Repo et al., 2011, 2014a, 2014b). In addition, the validity of the Yasso07 model has been tested specifically at boreal cropland sites. These tests suggest that this model is suitable for estimating the effects of organic amendments (Karhu et al., 2012) and those of afforestation and deforestation (Karhu et al., 2011) on the SOC pool. However, the validity of a modeling approach based on the Yasso07 model at a larger regional scale remains to be tested.

The first objective of this study was to find out reasons for the decreasing trend in the SOC pool of Finnish croplands. The second objective was to evaluate the suitability of an approach based on the Yasso07 model for estimating the pool of SOC and changes in this pool in boreal croplands at a regional scale.

2. Materials and methods

2.1. General description of the study

Finnish croplands cover 2.2 million ha of land and are mainly located in the southern and western parts of the country (Fig. 1). We divided these croplands into four geographical regions (south, west, east and north) and simulated the SOC budget of the croplands in each region between 1900 and 2009 using the Yasso07 soil carbon model. We excluded organic croplands from this study since the model is applicable for mineral soils only. To test the validity of the simulation results, we compared them to measurements of the pools and the temporal trends of SOC. To study reasons for the observed decline in the SOC pool, we carried out a sensitivity analysis.

2.2. The Yasso07 model

The Yasso07 soil carbon model is based on three assumptions of litter decomposition. According to the first one, litter consists of four

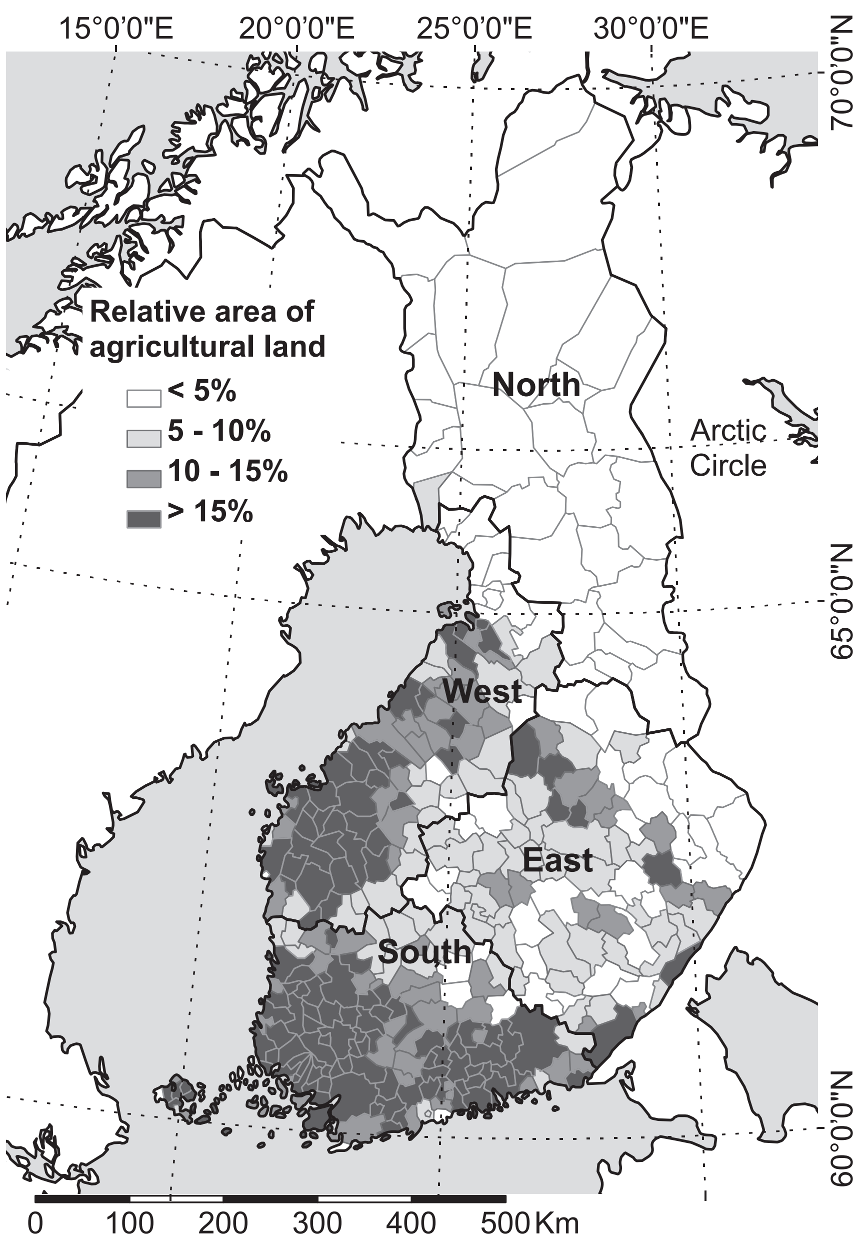

Fig. 1. The croplands in Finland and the study regions of this research.

compound groups, namely compounds 1) soluble in a non-polar solvent, ethanol or dichloromethane (denoted using E), 2) soluble in water (W), 3) hydrolyzable in acid (A) and 4) neither soluble nor hydrolyzable at all (N). Each group has its own decomposition rate independent of a plant species the litter originates from. According to the second assumption, the decomposition rates of these compound groups depend on temperature and precipitation. According to the third assumption, the decomposition of the compound groups results in mass flows both out of the system and between the compound groups and, in addition, formation of more recalcitrant humus (H). The decomposition of woody litter depends additionally on its diameter (Tuomi et al., 2011a). We used the same parameter values of the model in this study as were used in previous agricultural applications (Karhu et al., 2011, 2012). The simulated estimates represented soil layers above the depth of 1 m.

2.3. Model simulations

We simulated the development of the SOC pool in the croplands for 110 years, from 1900 to 2009, and studied the changes in this pool in detail during the last 35 years, from 1974 to 2009, in each study region. The last 35 years were studied in detail, because the simulated estimates of the SOC pool and the changes in this pool were compared to data from a national monitoring network of cropland soils (Heikkinen et al., 2013). This network was established in 1974 and resampled in 1987, 1998 and 2009 (Mäkelä-Kurtto and Sippola, 2002; Sippola and Tares, 1978).

The 110-year simulation period was selected for two reasons. Firstly, it represents a typical age of Finnish croplands since large areas of forested land were converted to cropland at the turn of the 20th century (Markkola, 2004). Secondly, most of the pool of SOC accumulated during the pre-cropland forest is at least hundreds of years old, reaching a new steady state only in a decadal or centennial time scale after land use change (Jenkinson and Rayner, 1977; Liski et al., 1998; Trumbore, 1997).

To start the simulations, we assumed that the SOC pool was in a steady state with litter input from forest covering the land before establishing the croplands. After this, we estimated carbon input to the soil based on statistics of crop yield and livestock number (IPCC, 2006; Tike, 2013). We used today's carbon input and assumed that it stayed constant throughout the simulation period because of the lack of more detailed data. However, because the levels of carbon input and probable upward trends in it were uncertain, we studied their effects on the simulation results in a sensitivity analysis.

A sensitivity analysis of the simulations was carried out only in the southern study region. This was adequate because the modeling setup was similar in each study region and consequently the results of the sensitivity analysis were also essentially similar. The southern region was chosen because most Finnish croplands are located in the southern part of the country (Fig. 1). The sensitivity analysis served two purposes. Firstly, it helped to elucidate the effects of uncertainty in the model input values on the simulation results. Secondly, it helped to identify the model input variables the simulation results were most sensitive to. This made it possible to study reasons for the downward trend in the SOC pool of the croplands observed in soil inventories earlier (Heikkinen et al., 2013).

We changed four variables, which we considered to be the most relevant, in the sensitivity analysis. The magnitude of the changes was chosen based on the estimated range of uncertainty in these input variables. First, we altered carbon input to the soil of the forest preceding cropland by 25% upward and 25% downward. This covers the approximate uncertainty in the litter production estimates caused by possible wildfires, slash-and-burn cultivation, forest pasturing, and measurement errors (Heikinheimo, 1915; Liski et al., 1998). Second, we altered carbon input to the soil of the croplands during the simulation period by 50% upward and 50% downward. This uncertainty in the cropland litter input was approximated based on the confidence intervals of the parameters (harvest index, shoot to root ratio etc.) as presented in IPCC guidelines (IPCC, 2006). Third, we introduced upward trends in the carbon input to the cropland soil during the simulation period (linear trends, input in 1900 4/5, 3/5 and 2/5 of the input in 2009, corresponding to the 25, 67 and 150% increase between 1900 and 2009). The steepest upward trend is based on an observed increase of about 100–150% in cereal yields between 1920 and 2010 (Tike, 2013). Fourth, we applied increasing trends in the annual mean temperature over the simulation period (0.5 and 1.0 °C linear warming over the last 110 years) based on observed warming trends in Finland (Tietäväinen et al., 2010). We did not include the chemical quality of agricultural litter to the sensitivity analysis because the decomposition rates of different agricultural litter are fairly similar (Karhu et al., 2012).

2.4. Model input data

2.4.1. Forest preceding cropland

Carbon input to the soil of the pre-cropland forests (Table 1) was estimated based on growth and yield tables which represent the best knowledge of the natural Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) stands in the early 1900s when large areas of croplands were established (Koivisto, 1959). As croplands were established on the most productive land, we used data for a moist and productive forest type (OMT) in the southern, western and eastern study regions, and data for a semi-arid forest type (EVT) in the northern study region (the Finnish forest types according to Cajander (1925) and Kalela (1961)). The data tables are based on original studies by Ilvessalo (1920, 1937). The tables are based on 50 OMT and 24 EVT forest stands, out of altogether about 600 stands.

To estimate an average carbon input to soil at the pre-cropland forest sites, we calculated the annual estimates of litter production over a forest succession based on the growth and yield tables and added standing biomass at the end of succession to these litter production estimates. Stem biomass of standing trees was, however, excluded from the estimates of the soil carbon input because we assumed that the stem wood was usually removed from these otherwise unmanaged forests and used for construction or heating.

We calculated the litter production of forest using the same method as is used in the national greenhouse gas inventory of Finland (NIR, 2012). The annual values of stem wood volume obtained from the growth and yield tables were converted to the biomass of tree components (needles, branches, stem, stump, coarse roots and fine roots) using allometric biomass equations (Repola, 2009). The litter production of these components was calculated by multiplying the biomass values by component-specific turnover rates (Liski et al., 2006). For the litter production of ground vegetation, we applied the values used in the national greenhouse gas inventory of Finland (Laiho et al., 2003; Muukkonen and Mäkipää, 2006).

Table 1
Input of carbon to the soil of the forests preceding the croplands in the study regions.

Litter component	Study region	
	South, west, east	North
	Input of carbon (Mg C ha^{-1} $year^{-1}$)	
Needles	0.878	0.406
Fine roots	2.206	0.933
Coarse roots	0.410	0.299
Branches	0.322	0.262
Dead stems	0.228	0.289
Living stems	0	0
Dead stumps	0.016	0.021
Living stumps	0.044	0.028
Ground vegetation	0.506	0.666
Total	4.655	2.904

The carbon concentration of litter was assumed to be 50%. For the chemical quality of litter (Table 3), in terms of the AWEN fractions the Yasso07 model uses (see Section 2.2), we applied the same values that are used in the national greenhouse gas inventories of Finland and Sweden (NIR, 2012; Ortiz et al., 2013; Sievänen et al., 2013). We used 2 cm for the diameter of branch litter and 8.4 and 9.0 cm respectively for living and dead stems; this information was also needed for the Yasso07 model simulations. The branch diameter was the same as that used in the national greenhouse gas inventory for fine woody litter (NIR, 2012) and the stem diameters were calculated based on the growth and yield tables (Koivisto, 1959).

2.4.2. Cropland

Carbon input to the soil of the croplands (Table 2) consisted of plant residues and manure. We applied a national method to estimate it (Palosuo et al., 2014, unpublished results).

The carbon input of plant residues was estimated based on the statistics of crop yields between 1998 and 2009 (Tike, 2013). The yield data were converted to carbon input according to a calculation method proposed by Bolinder et al. (2007) using Finnish conversion factors. Aboveground carbon input was estimated based on annual yield, harvest index, dry matter content and carbon concentration. Belowground carbon input was estimated based on a shoot-to-root ratio (annual crops) or root biomass (perennial crops) and a root turnover rate. The calculation method and the conversion factors are described in detail in another study (Palosuo et al., 2014, unpublished results). We included the most important annual (wheat, rye, barley, oat and rape) and perennial (hay and silage) crops in our calculation.

The carbon input of manure was estimated based on the number of livestock in 2009 (Tike, 2013) and manure excretion per head of livestock (IPCC, 2006). The chemical quality of the plant residues and manure (Table 4) were taken from an earlier study on agricultural fields (Karhu et al., 2012).

2.4.3. Climate

We used region-specific average values of precipitation, mean annual temperature and temperature amplitude (the difference between the average temperatures of the warmest and the coldest month) in the simulations. These values were calculated from a 10 × 10 km gridded dataset of the Finnish Meteorological Institute (Venäläinen et al., 2005). The dataset was based on monthly observations. We used the actual yearly values for years from 1970 to 2009 and mean values of years 1970 to 1999 for years before 1970 because of missing data (Table 5).

3. Results

The SOC pool of the croplands declined in each study region over the entire study period from 1900 to 2009 according to the simulations (Fig. 2). This was because the decomposition of forest-originating carbon exceeded the accumulation of agriculture-originating carbon in the soil. The mean estimate of the decrease rate ranged from 0.29 to 0.36 Mg ha^{-1} year^{-1} among the study regions during the last 35 years of our study period (Fig. 2). The mean estimate for the SOC pool of the croplands ranged from 92 to 124 Mg ha^{-1} among the study regions at the end of the study period in 2009 (Fig. 2). The reliability of these estimates and reasons for the downward trend were studied using a sensitivity analysis.

Table 2
Input of carbon to the soil of the croplands in the study regions. Total carbon input per hectare was calculated as a sum of annual and perennial crop residues, weighted by the cultivated area, and manure.

Input component	Study region			
	South	West	East	North
	Input of carbon (Mg C ha^{-1} year^{-1})			
Annual crop residue	1.754	1.293	0.792	0.185
Perennial crop residue	0.285	0.594	0.933	1.454
Manure	0.210	0.378	0.469	0.508
Total	2.249	2.265	2.194	2.147

Table 3
The chemical quality of forest litter input.

Plant litter component	Proportions of AWEN fractions			
	A	W	E	N
Needles	0.473	0.114	0.041	0.372
Fine roots	0.551	0.133	0.067	0.250
Coarse roots	0.475	0.019	0.078	0.430
Branches	0.475	0.019	0.078	0.430
Dead stems	0.473	0.114	0.041	0.372
Living stems	0.473	0.114	0.041	0.372
Dead stumps	0.473	0.114	0.041	0.372
Living stumps	0.473	0.114	0.041	0.372
Ground vegetation	0.557	0.2253	0.0867	0.131

The simulated estimates of the decrease rate were the most sensitive to the litter production of forest before establishing the croplands and a possible upward trend in the agricultural litter production (Fig. 3). Decreasing or increasing the forest litter production by 25% respectively lowered or enhanced the mean estimate of the decrease rate by 29% during the last 35 years of the study period. An upward trend in agricultural litter production slowed down the decrease rate estimates by 14 to 38% depending on the slope of the trend. On the other hand, the overall level of agricultural litter production or raising temperatures had only small effects on the simulated estimates of the decrease rate of the SOC pool. Changing the level of the agricultural litter input by as much as 50% changed the mean decrease rate estimate by only 7.5%. A 0.5 or 1 °C linear warming over the simulation period increased this estimate by 4 or 8%, respectively.

The simulated estimate for the SOC pool of the croplands was also very sensitive to the litter production of the pre-cropland forest (Fig. 4). Increasing or decreasing this variable by 25% changed the mean SOC pool estimate by 18% in the same direction at the end of the simulation period in 2009. The other important factor affecting the estimates of the SOC pool was the litter production of the croplands. Altering this litter production up or down by 50% changed the mean SOC pool estimates by 14% in the same direction. The trends in the litter production of the croplands or those in temperature had only very small effects on the simulated SOC pool estimates.

4. Discussion

4.1. Evaluation of the method

An approach based on the Yasso07 model was used in this study to analyze reasons for the decreasing trend observed in the SOC pool of Finnish croplands (Heikkinen et al., 2013). An important prerequisite for the usefulness of this approach and the reliability of the conclusions is the validity of the simulated results in the light of measurements.

The simulated estimates of the pool of SOC in the forest preceding croplands were comparable with measurement-based estimates taken in forests adjacent to croplands today (Karhu et al., 2011). In the pre-cropland forest in 1900, the simulated mean estimate of the SOC pool

Table 4
The chemical quality of carbon input to the cropland soils.

Input component	Proportions of AWEN fractions			
	A	W	E	N
Annual crop	0.740	0.094	0.021	0.144
Perennial crop	0.451	0.358	0.034	0.157
Manure	0.645	0.123	0.072	0.161

Table 5
Climate of the study regions (means of 1970–1999). Amplitude means the difference between the mean temperatures of the warmest and coolest months.

Study region	Annual precipitation (mm)	Annual temperature (°C)	Amplitude (°C)
South	637	4.2	12.7
West	565	2.5	13.5
East	629	2.7	14.2
North	552	−0.7	14.8

in the 100 cm deep soil layer was 159 to 191 Mg ha^{-1} depending on study region (Fig. 2). This simulated estimate of the southern study region varied from 120 to 199 Mg ha^{-1} according to the range of the sensitivity analysis (Fig. 4). The mean of the measurements in the forests adjacent to croplands today, taken from a 40 cm deep soil layer, was 113 Mg ha^{-1}, varying between 92 and 165 Mg ha^{-1} (Karhu et al., 2011). In the productive forest type (OMT), assumed to have covered the soil before establishing the croplands, the 40–100 cm deep soil layer contains approximately 30% of the amount of carbon in the 0–100 cm layer (Liski and Westman, 1995). Thus the 0–100 cm deep soil layer of the next-to-cropland forests would contain approximately 147 Mg ha^{-1}, ranging from 120 to 215 Mg ha^{-1}. This is quite similar to our simulation results.

The simulated estimates of the SOC pool in the pre-cropland forests were higher than simulated or measured estimates in today's forests in general (Liski et al., 2006; Ortiz et al., 2013; Rantakari et al., 2012). This was caused by the high litter production values calculated based on the old growth and yield tables of natural forests (Koivisto, 1959). According to these tables, the earlier fully stocked forests carried more biomass than the modern, frequently thinned ones. Consequently, they were estimated to produce more litter. In addition, the measured estimates of the SOC pool are not directly comparable with the simulated estimates, as the latter also include the coarse woody litter pool consisting of stems and stumps.

Like in the pre-cropland forest, the simulated estimates of the SOC pool in the croplands were comparable with the measurement-based estimates. In the croplands in 2009, the simulated mean estimate of the pool of SOC in the 100 cm soil layer ranged from 92 to 124 Mg ha^{-1} among the four study regions. This estimate varied from 76 to 109 Mg ha^{-1} according to the range of the sensitivity analysis in the southern study region (Figs. 2 and 4). According to the results of national soil inventories, the pool of SOC in a 15 cm soil layer in 2009 ranged from 51 to 62 Mg ha^{-1} among the four study regions, varying between 47 and 67 Mg ha^{-1} according to the 95% confidence intervals (Heikkinen et al., 2013). According to the soil profile studies available in Finland, the 15–100 cm deep soil layer contains 50 to 67% of the amount of carbon in the 0–100 cm soil layer (Yli-Halla et al., 2000). Thus the 0–100 cm deep soil layer would contain approximately 71 to 112 Mg C ha^{-1}. This range is similar to the variability among our study regions and the range of the sensitivity analysis.

The SOC pool of the croplands decreased between 1974 and 2009 in each study region according to both the model simulations and the measurements (Fig. 2). The simulated decrease rates were, however, in general somewhat higher than the measurement-based estimate calculated based on the national soil inventories (Heikkinen et al., 2013). The simulated mean estimate for the decrease rate of the SOC pool in the 100 cm soil layer was 0.29 to 0.36 Mg ha^{-1} year^{-1} between 1974 and 2009 among the four study regions. This estimate varied from 0.18 to 0.38 Mg ha^{-1} year^{-1} according to the range of the sensitivity analysis in the southern study region. The measured mean estimate of the SOC change in a 15 cm soil layer across the whole country was equal to 0.22 Mg ha^{-1} year^{-1} during the same period (Heikkinen et al., 2013). This is about 30 to 60% lower than the simulated mean estimates depending on study region. However, the lower end of the

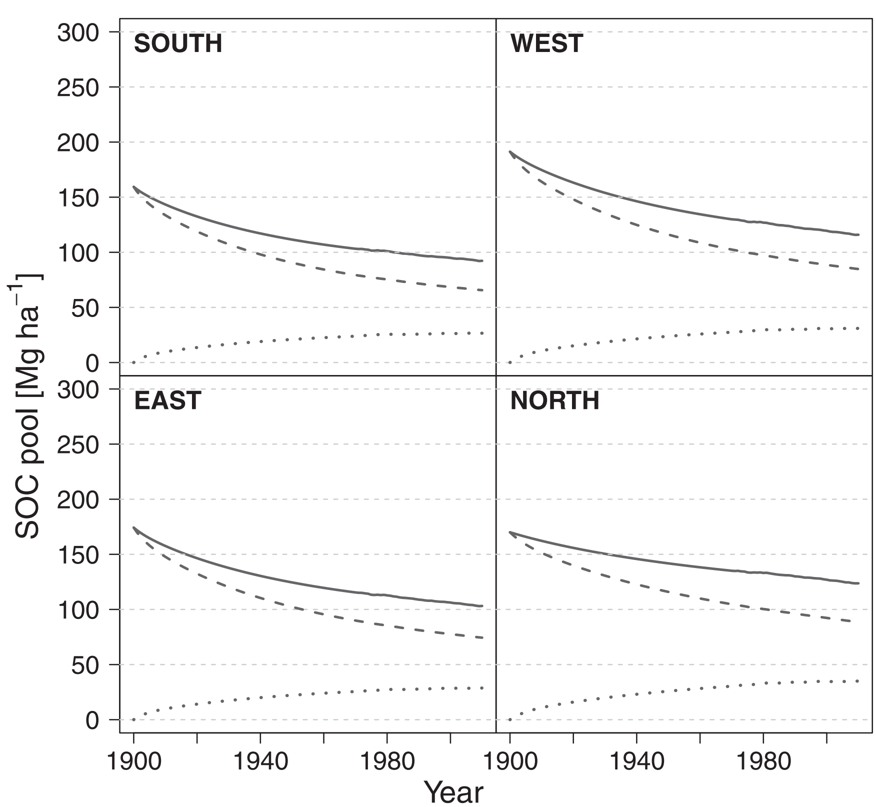

Fig. 2. Simulated SOC pools in the croplands of the study regions during the study period from 1900 to 2009. The total carbon pool (uniform line) is the sum of the SOC pool originating from forest before establishing the croplands (dashed line) and the SOC pool accumulated while practicing agriculture (dotted line).

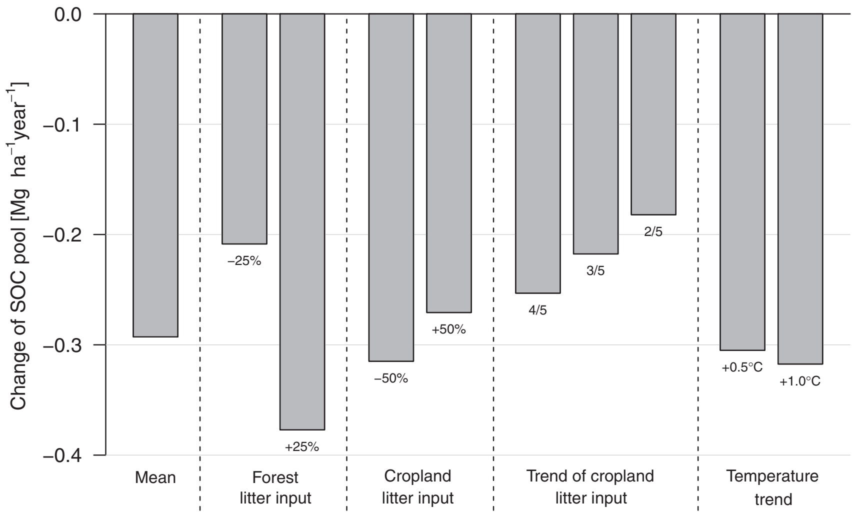

Fig. 3. The sensitivity of the simulated change in the SOC pool of the croplands of the southern study region between 1974 and 2009 to 1) the quantity of forest litter input, 2) the quantity of agricultural litter input, 3) increasing trends in the agricultural litter input (linear trends over the study period from 1900 to 2009, agricultural litter input in 1900 4/5, 3/5 or 2/5 of the input in 2009) and 4) increasing trends in temperature (linear trends over the study period from 1900 to 2009, mean annual temperature in 1900 0.5 or 1.0 °C lower than in 2009).

sensitivity analysis results was quite similar to the measured estimate (Fig. 3). It was difficult to compare the simulated and measured SOC change in more detail because no measurements of the SOC change below topsoil are available in Finland. However, the changes of SOC in the 100 cm soil layer are likely greater than those of the 15 cm layer because of the larger SOC pool. In this regard our simulated estimates of the SOC change seem reasonable.

Even though direct comparisons were partly difficult, the similarity of the simulated and measured estimates of both the SOC pool and the SOC changes gives support to the suitability of the methodology for

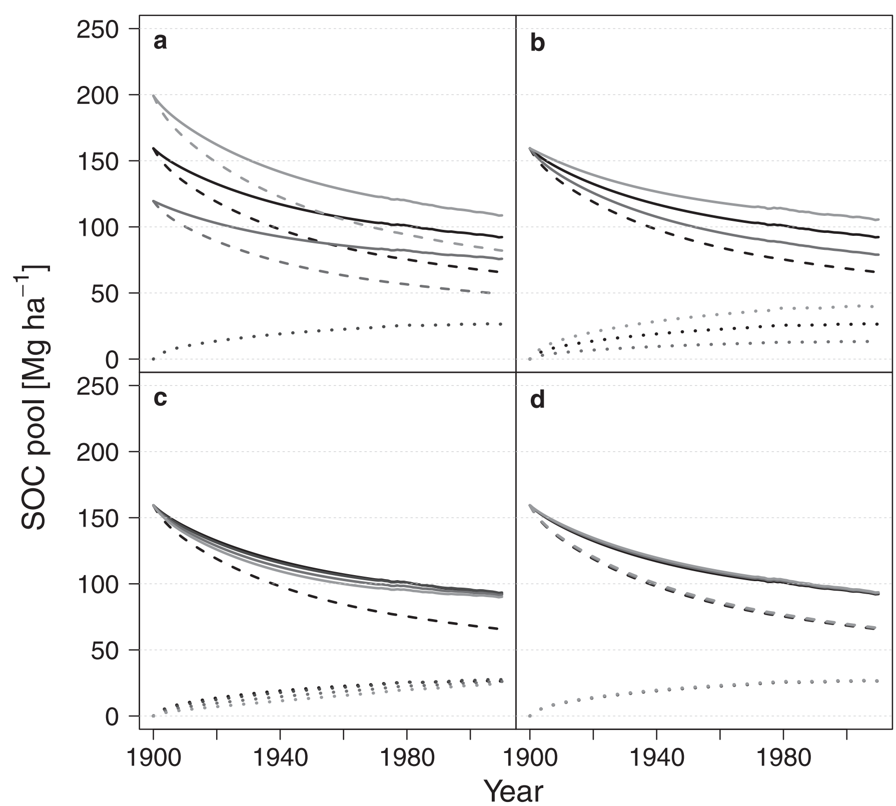

Fig. 4. The sensitivity of the simulated SOC pool in the croplands of the southern study region during the study period from 1900 to 2009 to the same factors as in Fig. 3, namely (a) the quantity of forest litter input, (b) the quantity of agricultural litter input, (c) increasing trends in the agricultural litter input and (d) increasing trends in temperature. The figures show the total SOC pool (uniform lines), the SOC pool originating from forest before establishing the croplands (dashed lines) and the SOC pool accumulated while practicing agriculture (dotted lines). (a) The gray lines above and below the black lines (mean litter input) refer to the 25% increase or decrease in the forest litter input, respectively. (b) The gray lines above and below the black lines (mean litter input) refer to the 50% increase or decrease in the agricultural litter input, respectively. (c) The highest gray lines below the black lines (constant litter input) refer to the most gradual increasing linear trend in the agricultural litter input (input in 1900 4/5 of the input in 2009) and the lowest gray lines refer to the steepest increasing linear trend in the agricultural litter input (input in 1900 2/5 of the input in 2009). (d) The gray lines above the black lines (mean temperature) refer to 0.5 or 1.0 °C linear trends in temperature over the study period.

analyzing reasons for the decreasing trend in the SOC pool of Finnish croplands.

4.2. Reasons for the decreasing SOC

According to this study, the pool of SOC in Finnish croplands has been declining because the decomposition of forest-originating carbon has exceeded the accumulation of agriculture-originating carbon in the soil (Fig. 2). This is due to two reasons. Firstly, the litter production of cropland is smaller than that of forest. Secondly, the agriculture-originating litter decomposes faster than the forest-originating litter especially because the former lacks the slowly decomposing component of woody litter. Forest-originating woody litter contains also recalcitrant lignin-like compounds in higher concentrations than agriculture-originating litter does (Tables 2 and 3).

Croplands produce less litter than forests mainly because a considerable part of the NPP, often 40 to 60%, is extracted as harvest (Hay, 1995). In southern Finland, the estimated NPP of the croplands was on average 3.4 Mg C ha^{-1} $year^{-1}$; we estimated the NPP by summing up the annual litter production and harvest (Table 2). The estimated NPP of the pre-cropland forest was on average 5.3 Mg C ha^{-1} $year^{-1}$ when the litter production of standing trees was included. The NPP of cropland is lower than that of forest also when the possible uncertainty in the litter production values is taken into account. Because a considerable part of the NPP in cropland is extracted as harvest, our conclusion about the main reason for the loss of SOC in Finnish croplands seems reasonable. Similar to our results, Leifeld (2013) suggests the high harvested fraction of organic matter from agricultural systems as the major reason for declining SOC pools in croplands.

A decline in the pool of SOC in croplands in past decades has also been observed elsewhere in Europe in repeated regional and national scale monitoring studies (e.g. Bellamy et al., 2005 in England and Wales; and Lettens et al., 2005; Meersmans et al., 2009; Sleutel et al., 2006 in Belgium). These studies have suggested climate change (Bellamy et al., 2005), changes in organic matter input from animal manure and crop residues (Lettens et al., 2005; Sleutel et al., 2006) increase in the plow depth and changes in crop rotation (Meersmans et al., 2009) as the main reasons for the observed SOC changes. Regional studies of the SOC change in the whole 100 cm soil profile are rare. Our simulated estimate for the decrease of cropland SOC in southern Finland, 0.18 to 0.38 Mg ha^{-1} $year^{-1}$, overlaps with the mean of a measurement-based estimate taken in northern Belgium, 0.19 Mg ha^{-1} $year^{-1}$ (Meersmans et al., 2009).

According to our results, climate warming has not been a significant driving force of the changes in the SOC pool of croplands to date. The trend of air temperature increasing by 1 °C over the last 110 years, which is close to the observed one (Tietäväinen et al., 2010), did not have notable effects on the SOC pools nor changes in them (Figs. 3 and 4). Our results support those of Smith et al. (2007) who claimed in their modeling study that climate change could not be the main reason for the observed decline in the SOC pool of croplands in England and Wales, as suggested by Bellamy et al. (2005) earlier. The decline was more likely attributable to changes in agricultural management practices, such as decreased organic manure application and increased residue removal, and effects of historical land use change (Smith et al., 2007; van Wesemael et al., 2010).

Soil properties such as clay content and agricultural practices such as tillage, fertilizing and liming, affect also the changes in the SOC pool of croplands but the soil carbon model we used in this study did not take these effects into account. Clay particles stabilize SOC on their surfaces and slow down decomposition, and some soil carbon models include clay content as input information affecting the decomposition of litter and SOC (Jenkinson and Rayner, 1977; Parton et al., 1987). Our study may overestimate the decomposition rate of SOC in clay-rich soils because we did not account for this effect in our modeling. However, in a previous agricultural application of the Yasso07 model, other affecting factors were dominant and no correlation was found between soil texture and SOC pool (Karhu et al., 2011). Consequently, the authors concluded that it was possible to model SOC changes resulting from land-use change in these soils even without information on clay content (Karhu et al., 2011).

Tillage accelerates decomposition by improving soil aeration and breaking up aggregates, and the effect of reduced tillage on the enhanced accumulation of SOC is widely recognized (Mikha and Rice, 2004; West and Post, 2002). Nitrogen fertilization affects the SOC pool on the one hand by increasing the input of plant residues to soil due to increased plant production, and on the other hand by directly affecting the decomposition of soil organic matter (Alvarez, 2005). Our approach is limited in predicting SOC changes due to tillage or nutrient additions because these factors are not accounted for by the model. On the other hand, the results of an earlier validity test of our modeling approach in similar agricultural soils suggest that the majority of the tillage and nutrient effects on SOC are explained by the effects on plant productivity and consequently carbon input to soil (Karhu et al., 2011). These effects were accounted for in the present study.

We argue that it is possible to obtain useful information on the regional changes in the pool of SOC in the boreal croplands we studied using a simulation model combined with information on the carbon input and climate. Using this approach, we were able to evaluate the role of possible reasons for the observed decline in the SOC pool of Finnish croplands. The major uncertainties in the results were caused by uncertainty about the model input values. Our study shows that the drivers of change in the SOC pool of croplands can be best detected via process-based models, whereas field measurements are invaluable in testing the validity of the simulated results.

According to our study, the loss of SOC from Finnish croplands could be slowed down by management practices that increase the carbon input to the soil. Application of organic manure and avoiding bare fallow are potential means to increase the carbon input to cropland soil in Finland. These practices have indeed increased the pool of SOC elsewhere according to field experiments (Diacono and Montemurro, 2010; Freibauer et al., 2004). The effects of different management practices on the development of the SOC pool in croplands can be estimated using our approach presented here.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.geodrs.2014.09.003. These data include Google maps of the most important areas described in this article.

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