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Research article

High organic carbon content constricts the potential for stable organic carbon accrual in mineral agricultural soils in Finland

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ABSTRACT

Sequestering carbon into agricultural soils is considered as a means of mitigating climate change. We used agronomic soil test results representing c. 95% of the farmed land area in Finland to estimate the potential of the uppermost 15 cm soil layer of mineral agricultural soils to sequester organic carbon (OC) and to contribute to the mitigation of climate change. The estimation of the maximum capacity of mineral matter to protect OC in stable mineral-associated form was based on the theory that clay and fine-sized (fines = clay + silt) particles have a limited capacity to protect OC. In addition, we used the clay/OC and fines/OC ratios to identify areas with a risk of erosion and reduced productivity, thus indicating priority areas potentially benefitting from the increased soil OC contents. We found that 32–40% of the mineral agricultural soils in Finland have the potential to further accumulate mineral-associated OC (MOC), while in the majority of soils, the current OC stock in the uppermost 15 cm exceeded the capacity of mineral matter to protect OC. The nationwide soil OC sequestration potential of the uppermost 15 cm in mineral agricultural soils ranged between 0.21 and 0.26 Tg, which corresponds to less than 2% of annual greenhouse gas emissions in Finland. The fields with the highest potential for SOC accrual were found in the southern and southwestern parts of the country, including some of the most intensively cultivated high-clay soils. Although the nationwide potential for additional OC sequestration was estimated to be relatively small, the current OC storage in Finnish arable mineral soils (0-15 cm) is large, 128 Tg. Farming practices enabling maximum OC input into the soil play an important role as a tool for mitigating the loss of carbon from high-OC soils in the changing climate. Furthermore, especially in high-clay areas with potential for MOC accrual, efforts to increase soil OC could help improve soil structural stability and therefore reduce erosion and the loss of nutrients to the aquatic environments.

1. Introduction

Many countries globally face great challenges in meeting the international and national targets set for the mitigation of climate change. The European Union plans to achieve carbon neutrality by 2050 through the European Climate Law. As a member state, Finland faces a challenge in identifying feasible and cost-effective means to meet the European Union's climate targets, especially for the land use, land-use change, and the forestry sector (LULUCF). The target for the national net sink of this sector is −17.8 Mt CO_2-eq by 2030. In 2021, the LULUCF sector was a net source of greenhouse gas emissions (0.6 Mt CO_2-eq) (Official Statistics of Finland, 2023). One way to contribute to achieving this goal would be to sequester carbon into agricultural soils. Increasing soil organic carbon (OC) content has been promoted for its potential in

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climate change mitigation (Minasny et al., 2017; Lal, 2004) but it is also well known that OC as part of organic matter (OM) plays a crucial role in many soil functions supporting primary production, biodiversity, erosion protection, and contributing to the regulation of water cycles (Hoffland et al., 2020; Lal, 2004). Soil OC stocks and contents in agricultural soils are higher in northern Europe than in central and southern parts of the continent (Matschullat et al., 2018). A cooler climate with freezing temperatures during the winter in addition to a shorter time since forest clearance for agriculture contribute to this difference (Heikkinen et al., 2013). Furthermore, the soil processes affecting OC are related to soil inherent properties like parent material and texture as well as topography and the water table level (Kögel-Knabner and Amelung, 2021). Globally, there is a substantial variation between the regions and soil types in the potential to sequester OC in soil (Zomer et al., 2017). The role of mineral agricultural soils (OM content <20%) in climate change mitigation and adaptation needs comprehensive approach: a consideration of local conditions, targeting the OC pool that persists, and estimating the potential for this pool to be increased, while stressing the prevention of further loss of OC from high-OM soils.

Chemical recalcitrance was long considered the main property driving the persistence and therefore the accrual of organic matter in soil. However, in recent decades, the role of soil mineral phase in protecting organic matter from degradation has been emphasized (Kögel-Knabner and Rumpel, 2018; Six et al., 2002; Hassink, 1997). Organo-mineral associations are established through the direct attachment of organic molecules to mineral surfaces via ligand exchange or electrostatic binding (Li et al., 2023). Instead of forming a monolayer, organic molecules probably sorb to minerals in patchy multilayered arrangements built through hydrophobic interactions and cation bridging (Kleber et al., 2007). Although this mineral-associated organic carbon (MOC) encompasses a fast-cycling pool, possibly involving the outer regions of the organo-mineral complexes, a large share is well protected and exhibits decadal to centennial mean residence times that indicate high stability (Guo et al., 2022; Kleber et al., 2007). On the contrary, the turnover of the non-protected OC fraction occurring as free particulate organic carbon (POC) is much faster, with mean residence times from years to decades (Guo et al., 2022; von Lützov et al., 2007). Furthermore, the POC fraction, being chemically and functionally different from the MOC, is more sensitive to environmental changes with respect to both losses and gains (Lavallee et al., 2020). In conditions with limited degradation, infinite accrual of POC is possible as evidenced by bogs. Considering MOC, a maximum level depending on the binding capacity of the minerals is expected (Castellano et al., 2015). When the OC attached to mineral particles has reached the maximum capacity of the mineral fraction to bind OC (MOC_{Max}), soil is considered to be saturated. Using global data, Georgiou et al. (2022) defined MOC_{Max} estimates of 86 ± 9 and 48 ± 6 mg C g^{-1} mineral matter for high- and low-activity minerals, respectively.

Several approaches to estimating the capacity of mineral matter to protect OC have been presented, while one of the most used relationships between soil fine-sized particles (<20 μm) and MOC was developed by Hassink (1997). Hassink (1997) estimated the MOC_{Max} assuming that grassland soils are saturated due to the high organic matter input. Later, similar equations for estimating the MOC_{Max} based on soil texture or mineralogy have been developed by Matus (2021), Cai et al. (2016), Feng et al. (2013) and Six et al. (2002). Dexter et al. (2008) proposed that OC can be protected by clay-sized particles in a mass ratio of 10/1 and clay soils not reaching the suggested maximum content of protected OC are prone to dispersion and have increased risk for erosion, thus relating OC saturation to soil structural stability. Dexter et al.'s (2008) findings were supported by Schjønning et al. (2012) and Jensen et al. (2019). Schjønning et al. (2012) further found a silt + clay (<20 μm) to OC ratio of 20 to serve as a threshold for soil dispersibility. Johannes et al. (2017) and Prout et al. (2021) developed the approach further and defined a clay to OC ratio of 13 as a threshold value above which there is a high risk for degraded soil structure. Thus, the optimal soil OC content that sustains soil health and functioning therefore probably depends on soil texture. Knowledge of OC content in relation to soil texture could help in targeting OC sequestration measures to support soil productivity as well as to mitigate the unwanted environmental impacts of crop production.

In this study, we applied the carbon saturation concept to estimate the stable OC saturation state of mineral agricultural soils in Finland. We aimed to estimate the potential of the uppermost managed layer (0–15 cm) of mineral agricultural soils to contribute to climate change mitigation through the sequestration of OC in mineral-protected form. In addition, we used ratios of clay to OC and fines to OC to identify areas with apparent OC deficiency and risk of structural deterioration making soil vulnerable to erosion and nutrient leaching, and thus, priority areas for improved management and climate change adaptation measures.

2. Material and methods

We estimated the stable OC accrual potential of arable mineral soils based on agronomic soil test results (Soil Test data, ST data) of c. 780,000 samples from Finnish farms analyzed in commercial soil test laboratories. The majority of Finnish farms (90% of farms, 92% of the farmed land area (Aakkula et al., 2012)) have participated in the Agri-environmental Programme obligating farms to analyze the soil fertility every fifth year. Farmers are instructed to take a representative composite sample that includes at least seven subsamples from the plough/tillage layer from every field parcel larger than 0.5 ha, and one soil sample cannot represent a larger area than 5 ha (Finnish Food Authority, 2015). Visible stones and litter should be removed.

The present study included ST data results from 2015 to 2019 and was therefore expected to cover the whole field area involved in the Agri-environmental Programme. Data are reported covering regions and municipalities within each region, except for the region of Åland where municipalities are not reported separately. Basic agronomic soil tests include information about soil type and organic matter, pH and electrical conductivity (EC) measured from an H_2O suspension (1:2.5 v:v), and plant available nutrients (P, Ca, Mg, K) extracted with an acidic (pH 4.65) ammonium acetate solution (Aac, Vuorinen and Mäkitie, 1955). Soil texture and content of organic matter (OM) are determined by feel (a finger assessment) and by the color and weight of the soil sample. Soils are classified based on OM content into four different classes listed in Table 1. Furthermore, mineral soils of glaciofluvial origin (sorted by water) are classified into textural classes according to the Finnish soil triangle (Fig. 1). Unsorted glacial tills are classified as moraine soils and are named after the dominant particle size (e.g., Silt Moraine).

The national soil monitoring data (NSM data) from 2018 were used to complement the information about soil texture and OC of samples included in ST data. The national soil monitoring network for Finnish agricultural soils covers the whole of Finland except the northernmost part of the country. It includes c. 600 sampling points of which 72 are classified as organic soils and are therefore not included here. A detailed description of the NSM network has been published in Heikkinen et al. (2021, 2013) and Keskinen et al. (2016). NSM data were used to extract information about particle size distribution (measured with the pipette method according to (Elonen, 1971)) within each soil type (Fig. 1). However, for clay soils, the clay content was estimated according to the

Table 1
Classification of mineral soils based on soil organic matter (OM) content assessed by feel in basic agronomic soil test and the corresponding organic carbon (OC) content.

Soil test assessment	OM%	OC%
Low	<3	1.7
Moderate	3–6	1.7–3.5
High	6–12	3.5–7.0
Very high	12–20	7.0–11.6

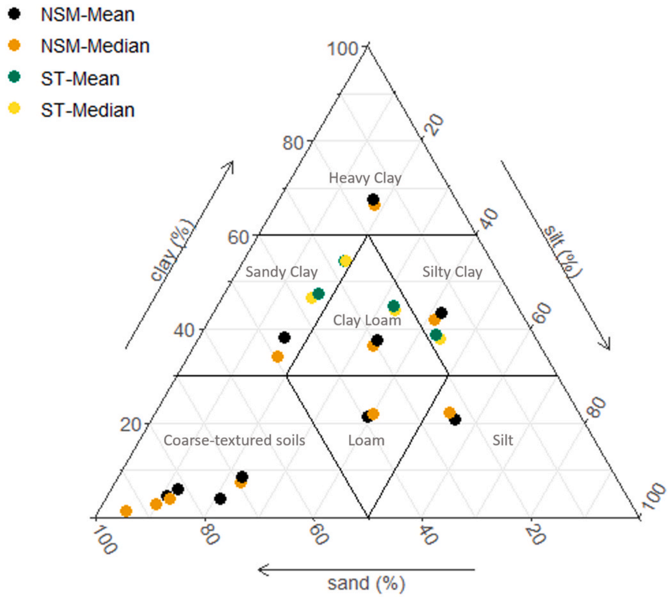

Fig. 1. The Finnish soil triangle, in which the clay refers to particles Ø<0.002 mm, silt to particles Ø 0.002-0.02 mm and sand to particles Ø 0.02-2 mm. Samples categorized as coarse-textured soils are further classified into four soil types based on the distribution of 0.02–0.06, 0.06–0.2, 0.2–0.6, and 0.6-2 mm-sized particles. The mean and median of clay, silt, and sand contents in each soil type in Finnish soil monitoring data (NSM data) and estimated from the Soil Test data (ST data) are marked. In visualization, the R package "ggtern" was used (Hamilton and Ferry, 2018).

pedotransfer function of Räty et al. (2021) as described in Section 2.1. If NSM data did not include information about particle size-distribution of a certain moraine soil type, we assumed the clay and fines contents to be similar to the sorted soil type with the same dominant particle size. In addition, NSM data were used to obtain more information about the distribution of OC content in soil within different OM classes. NSM data were complemented with other sources reporting OC content in Finnish mineral soils as described in Section 2.2.

2.1. Estimation of the maximum capacity of mineral matter to protect organic carbon

The maximum capacity of mineral matter to protect organic carbon (MOC_{Max}) was estimated using three different models. First, Dexter et al.'s (2008) theory suggests that OC can be sorbed onto the surfaces of clay sized particles in a ratio of 1to10, i.e.

$$\mathrm{MOC}_{\mathrm{Max}}^{\mathrm{Dex}} = 0.1\varphi_{\mathrm{c}}, \tag{1}$$

where φ_c is clay content, i.e., the mass fraction (or percentage) of clay particles. For coarse soils in ST data, ($\varphi_c < 30\ \%$), φ_c was taken to be the median clay content calculated over the measured φ_c from NSM data separately for silt and loam soils, and the four coarse soil types (Fig. 1). For clay soils ($\varphi_c \geq 30\ \%$), φ_c was estimated for each ST data point separately with the pedotransfer function of Räty et al. (2021) applicable only for clay soils, using soil pH and AAc-extractable K, Mg and Ca content reported in the ST data. The distribution of clay contents estimated from the ST data separately for each sample within each clay soil type are shown in Fig. 2.

In Schjønning's (2012) model, OC is protected by fine-sized mineral particles in a ratio of 1 to 20, resulting in

$$MOC_{Max}^{Schj} = 0.05\varphi_f = 0.05(\varphi_c + \varphi_s), \tag{2}$$

where φ_f is the fines content, and φ_s is the silt content. Clay content φ_c was calculated as above. For soils with clay content $\varphi_c < 30\ \%$, the fines content φ_f was estimated as the median of summed clay and silt content from the NSM data for each soil type separately. For soils with clay content $\varphi_c > 60\ \%$, the silt content was calculated based on the negative correlation between clay and silt in heavy clay soils,

$$\varphi_{\mathrm{s}} = -0.6856\varphi_{\mathrm{c}} + 63.807 \tag{3}$$

which is based on NSM (Supplementary material 1). For the remaining clay soils (classified as sandy clay, clay loam or silty clay), φ_s could not be estimated based on φ_c due to the poor correlation between these two size fractions, and the median silt content calculated over measured φ_s in NSM samples representing each soil type was therefore used (Fig. 1).

In Hassink's model (1997), the potential for soil to sequester OC onto mineral surfaces is calculated using the content of fines in soil as

$$\mathrm{MOC}_{\mathrm{Max}}^{\mathrm{Has}} = 0.037\varphi_{\mathrm{f}} + 0.407. \tag{4}$$

φ_f was determined similarly to Schjønning's model.

To obtain estimate of the average field area (A) that each soil test sample represented in different municipalities, the field area of each municipality (Luke) was divided by the number of all the soil test samples (including mineral and organic soils) from the area. The area of mineral soil fields was then calculated by multiplying the average field area represented by each soil test sample in the area/municipality by the number of mineral soil samples from the area/municipality. When calculated this way, the median size of the field that each soil sample represented varied between the regions from 1.95 ha to 3.97 ha (mean = 2.63 ha and median = 2.57 ha). According to Hiironen and Ettanen (2013), the mean plot size in Finland is c. 2.37 ha. Thus, the samples in each municipality or region were considered to represent similar-sized fields within the municipality or region in question, and the mineral soil samples included in the ST data were deemed to be reflective of the entire mineral soil field area within the respective municipality and region.

For each plot represented by one ST data sample, the bulk density at the OC saturation state (OC = MOC_{Max}) was estimated as in Heikkinen et al. (2013) as

$$\rho = 1.52\frac{\mathrm{kg}}{\mathrm{dm}^3} - 0.28\frac{\mathrm{kg}}{\mathrm{dm}^3}\ln(\mathrm{MOC}_{\mathrm{Max}}), \tag{5}$$

where MOC_{Max} is given as a percentage and equals one of the three estimates above. Finally, the maximum capacity of soil to protect organic carbon in mineral-associated form ($\mathrm{MOC}_{15\mathrm{cm}}$) in a 15 cm layer of topsoil was given by

$$MOC_{15cm} = V\rho\, MOC_{Max}\, A, \tag{6}$$

where $V = 15\ cm \times (100 \times 100)\frac{m^2}{ha} = 1500\frac{m^3}{ha}$ is the areal volume of the 15 cm layer, and A is the field area. The MOC_{15cm} estimate was calculated separately for all three MOC_{Max} estimates.

2.2. Estimation of the existing soil organic carbon stocks and calculating the OC accrual potential

To estimate of the existing soil organic carbon stocks in the 15 cm surface layer (SOC_{15cm}) we utilized the organic matter contents of the ST data classified into four organic matter classes. ST data are qualitative by nature and do not contain a numerical OC or OM estimate for each data point. Numerical information about the OC content distribution in Finnish mineral soils was extracted from NSM data and from Mattila and Rajala (2020), Soinne et al. (2021) and Soinne et al. (2023). The collected 660 measured OC contents were classified into four classes using the same threshold values for OM as in the ST data, as shown in Table 1. OM content was converted to OC content using the van Bemmelen factor of 1.724

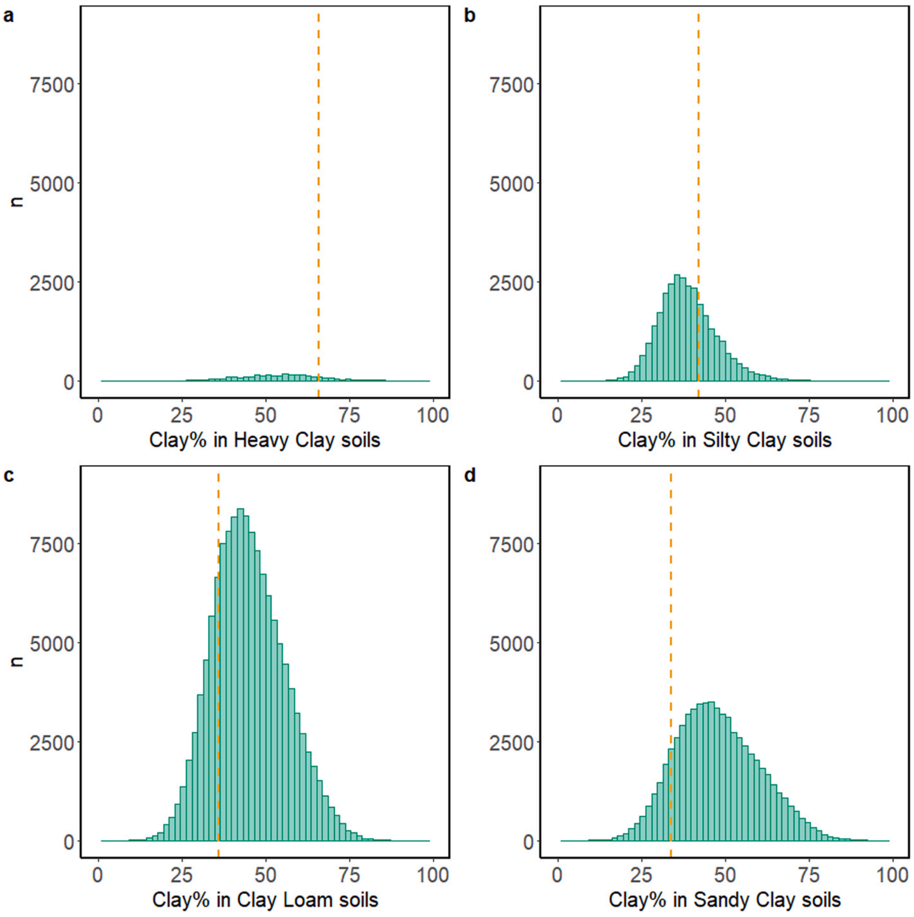

Fig. 2. Distribution of clay content estimated based on soil test data (ST data) within each clay soil type using the pedotransfer function of Räty et al. (2021) for clay soils. The orange vertical lines indicate the median calculated from the NSM data for each clay soil type (Fig. 1).

$$\mathrm{OC} = \frac{\mathrm{OM}}{1.724}, \tag{7}$$

where both *OC* and *OM* are given as percentages. This method has been found suitable for Finnish mineral soils (Heikkinen et al., 2021).

To take the distribution of OC contents in each qualitative OM class into account, a Monte Carlo scheme was applied. Here, each observation in the ST data was processed separately. First, a random OC content was sampled from the OC distribution (Fig. 3), corresponding to the OM class reported in the ST data. Then, the SOC_{15cm} represented by each ST data point was calculated similarly to Equation (6). The procedure was repeated to account for each observation within each municipality and region.

$$\mathrm{SOC_{15cm}} = \mathrm{V}\rho\ \mathrm{OC\ A}. \tag{8}$$

The process was repeated 10,000 times for each municipality and region to yield a set of SOC_{15cm} stocks, from which the mean and the standard deviation were determined for each municipality and region. However, we note that the only source of stochasticity in this setting is the OC within the OM class, and the standard deviations are therefore rather marginal.

The OC accrual potential reflecting the available mineral surfaces for the protection of OC was calculated for each ST data sample as the difference between the MOC_{15cm} estimates (MOC_{15cm}^{Dex}, MOC_{15cm}^{Schj} and MOC_{15cm}^{Has}) and the average SOC_{15cm} from the Monte Carlo simulation.

From the data we calculated the share of OC deficit samples ($SOC_{15cm} < MOC_{15cm}$) i.e., samples with potential to sequester OC in mineral protected form in each municipality and region. Further, for each municipality and region, we calculated the median OC saturation degree (SOC_{15cm}/MOC_{15cm}) of all samples, OC saturation degree of the OC deficit samples, and OC saturation degree of the OC saturated samples ($SOC_{15cm} > MOC_{15cm}$).

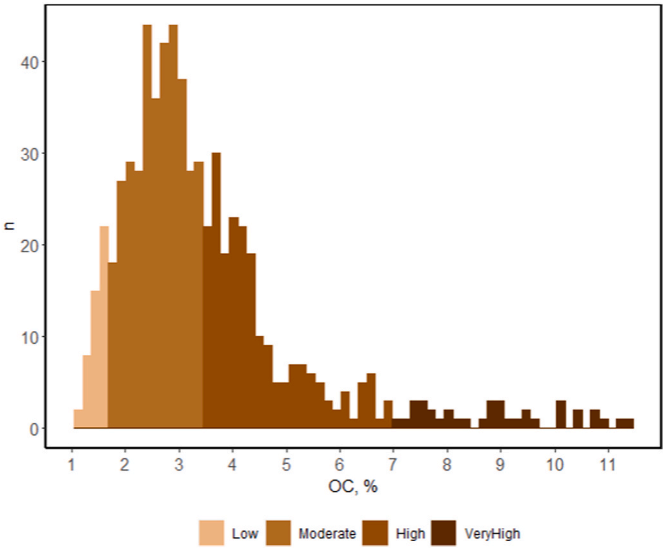

Fig. 3. Organic carbon (OC) content distribution within different OM classes in mineral soils in national soil monitoring (NSM) data complemented by the data sets of Mattila and Rajala (2020), Soinne et al. (2021) and (Soinne et al., 2023) (n = 660).

To estimate the field area of potentially structurally weak soils prone to erosion, we calculated the share of samples with a clay/OC ratio higher than 13 as suggested by Johannes et al. (2017) and Prout et al. (2021). The share of samples with an OC saturation degree below 65%, indicating samples with high potential for OC accrual (Guillaume et al., 2022) or higher than 135%, indicating a high saturation state that could indicate a high risk of OM mineralization were calculated for each municipality and are reported in Supplementary material 2.

The share of MOC of the total soil OC varies, and as there is only limited knowledge of the shares of MOC and POC in mineral agricultural soils in Finland with varying textural composition, the calculations were made assuming all soil OC to be MOC in soils with $MOC_{15cm} > SOC_{15cm}$. This assumption leads to an underestimation of the MOC accrual potential when the estimation is based on Hassink's equation, as some OC is inevitably in particulate form. If a 15% share of POC of total soil OC is assumed (Simonsson et al., 2014; Salonen et al., 2023), the underestimation of MOC accrual potential will affect samples in which OC saturation is below 117%. However, Dexter et al. (2008) and Schjønning et al. (2012), used total soil OC content when estimating the optimal clay/OC and fines/OC ratios, assuming that below the threshold values of 10 and 20 respectively, the protective capacity of mineral particles is exceeded.

3. Results

The nationwide SOC_{15cm} of mineral agricultural soils estimated based on the ST data results totalled 128 Tg. The estimated SOC_{15cm} in municipalities in Finland varied between 40 and 80 Mg ha^{-1} in the first 15 cm of mineral agricultural soils (Fig. 4), and of the 20 municipalities with the highest OC stocks, 11 were among those with the highest clay content, and 13 were among those with the highest fines content (Supplementary material 2).

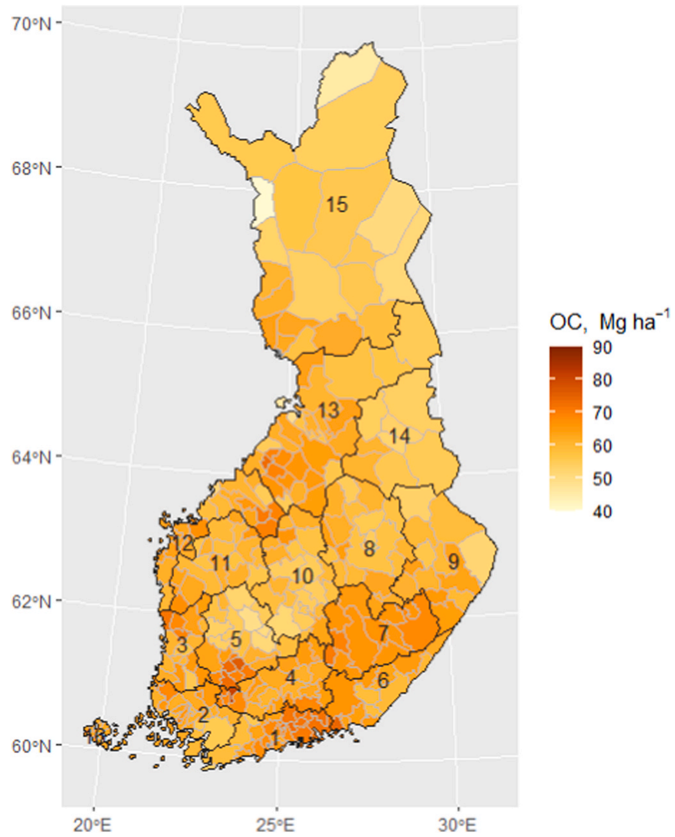

Fig. 4. Soil organic carbon (Mg ha^{-1}) in the uppermost 15 cm soil layer of mineral agricultural soils in each municipality (grey borders) estimated based on soil test data. The numbers refer to regions (black borders) listed in Table 2.

The highest total capacities for mineral matter to protect OC (MOC_{15cm}), calculated based on soil clay content (MOC_{Max}^{Dex}), were found in southern Finland with the largest share of clay soil fields (Fig. 5). When the capacity was calculated based on fine-sized particles (<20 μm, MOC_{Max}^{SCHJ}) by estimating OC saturation using a fines/OC ratio of 20, southern Finland was found to have lower total capacities. However, for areas with silty soils, this method gave higher MOC_{15cm} than when calculated based on clay content alone. In general, Hassink's method (MOC_{Max}^{HAS}) resulted in higher capacities than the other two methods mainly only in municipalities with the lowest mean fines content and thus more coarse-textured mineral soils (Supplementary material 2). In clay and silt soils, the MOC_{Max}^{HAS} resulted in lower capacities than when estimated with Dexter's or Schjønning's method.

The estimated mineral protected OC that could be accrued into the uppermost 15 cm of OC deficient soils in Finland varied between 0.21 and 0.26 Tg depending on the MOC_{max} calculation method (Table 2), being highest when calculated using Schjønning's method and lowest when using Hassink's method (Supplementary material 3) . Of the total field area of mineral agricultural soils in Finland, the field area with an OC saturation deficit was 40 and 39% when estimated using Schjønning's and Dexter's methods, respectively, and 32% when estimated based on Hassink's method. The majority of the OC deficit samples were from South- and Southwest Finland, whereas in northern and eastern Finland, less than 20% of the samples in different regions had the potential for stable OC accrual (Table 2, Fig. 6). Dexter's and Schjønning's methods indicated that there was potential for stable OC accrual and therefore potential for improved structural stability with an increase in OC content, especially in southern Finland (Fig. 6a and b). In addition, to identify areas with a high risk of structural deterioration, we calculated the share of samples with a clay/OC ratio higher than 13 as suggested by Johannes et al. (2017) and Prout et al. (2021). In coastal areas, a large share of the samples had clay/OC ratios higher than 13 (Fig. 7).

The OC saturation degree of the saturation deficit samples ($\mathrm{MOC_{15cm}} > \mathrm{SOC_{15cm}}$) was lowest in the southern Finland when the accrual capacity estimation was based on clay content (MOC_{Max}^{Dex}), but in many parts of Finland, the median OC saturation degree of the saturation deficit samples was nearly 90% (Supplementary material 3). When the accrual capacity estimations were based on fines contents (MOC_{Max}^{SCHJ} *and* MOC_{Max}^{Has}), the central parts of Finland showed somewhat lower OC saturation than when estimated based on clay contents, and therefore larger potential for OC accrual (Supplementary material 3).

The saturation degree of the OC saturated samples ($\mathrm{MOC_{15cm}} < \mathrm{SOC_{15cm}}$) was very high in Eastern and Northern Finland when MOC accrual capacity was estimated based on clay content (Fig. 8, a). When silt content was included and estimations of $\mathrm{MOC_{15cm}}$ was estimated based on fines contents, then the median saturation degrees were lower, but the median OC saturation degree was still largely over 200% (Fig. 8, b, and c, Supplementary material 3).

The difference between prevailing OC stock ($\mathrm{SOC_{15cm}}$) and MOC storage capacity ($\mathrm{MOC_{15cm}}$) in each municipality revealed that depending on the method used to estimate maximum capacity of the mineral matter to protect OC, only 1–28 out of 275 reported municipalities had net accrual potential exceeding their prevailing total OC stocks (Supplementary material 2). At the municipality and region levels, the higher $\mathrm{SOC_{15cm}}$ than $\mathrm{MOC_{15cm}}$ indicates that although there is OC accrual potential in individual field parcels, the majority of the field area has large OC stocks in relation to the protective capacity of the mineral matter (Table 2).

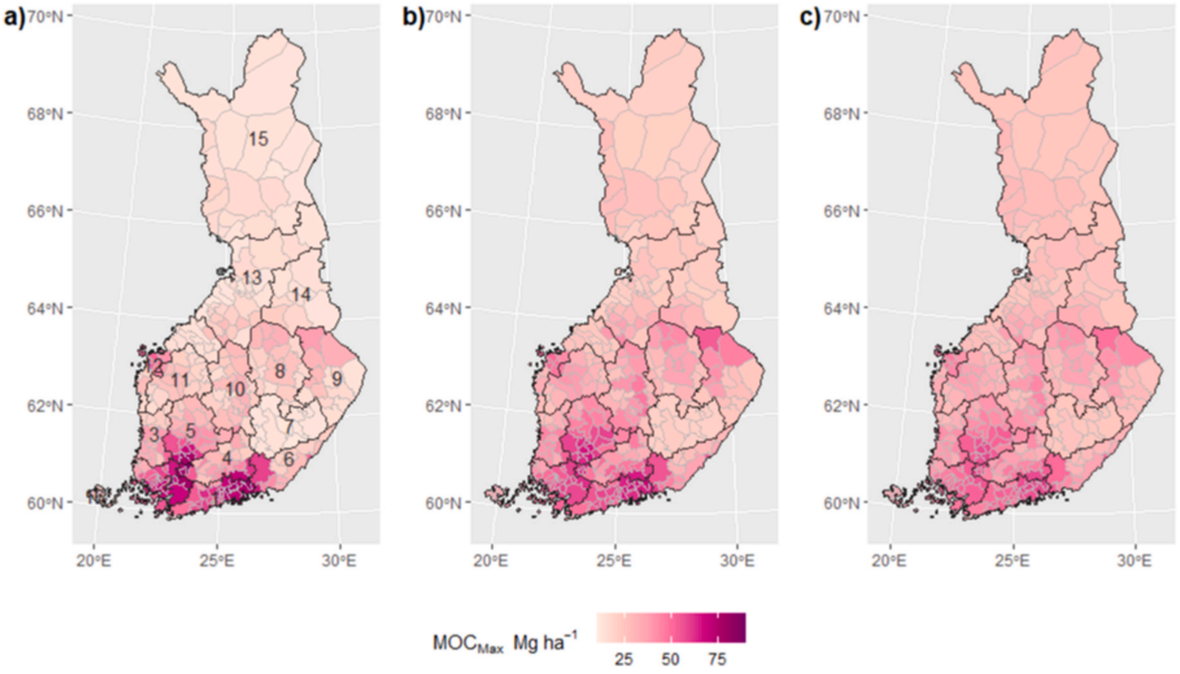

Fig. 5. Mineral-associated OC accrual capacity (MOC_{max}, Mg ha^{-1}) in the uppermost 15 cm soil layer estimated based on a) soil clay content according to Dexter et al. (2008) and fines (clay + silt) content according to b) Schjønning et al. (2012) and c) Hassink (1997) in each municipality of Finland (grey borders). The numbers refer to regions (black borders) listed in Table 2.

Table 2
Number of analyzed soil samples in Soil Test (ST) data and estimate of the mineral agricultural soil area and OC stocks (SOC_{15cm}, total and mean per hectare in the first 15 cm soil layer) in each region. Range of maximum capacity of the soil to protect OC in mineral-associated form in the first 15 cm soil layer (MOC_{15cm}), range of remaining OC accrual potential (=sum of OC accrual potential of OC deficit samples within each region), and range of median OC saturation degree of all samples as well as of samples, with OC deficiency (samples with OC accrual potential) when MOC_{Max} was estimated with three different calculation methods (Equations (1), (2) and (4)). See also Supplementary material 3.

Region		Number of samples	Field area estimate	SOC_{15cm} *	SOC_{15cm}/ A **	MOC_{15cm}	Median saturation degree	OC accrual potential	Share of samples with OC accrual potential	Median saturation degree of the samples with OC accural potential
		n	1000 ha	Tg	Mg ha $^{-1}$	Tg	%	Gg	%	%
1	Uusimaa	67,433	177	11.8	67	9.3–11.4	96–117	32–43	52–73	83–96
2	Southwest Finland	105,021	288	17.6	61	14.3–18.1	88–113	52–64	57–77	78–90
3	Satakunta	47,752	127	7.9	63	4.1–5.0	168–267	10–13	24–31	87–89
4	Häme	68,762	190	12.4	65	8.8–9.6	120–133	23–31	37–52	87–94
5	Pirkanmaa	62,789	160	9.8	61	7.8–8.7	104–122	25–33	48–64	87–88
6	Southeast Finland	46,682	116	7.4	64	4.8–5.0	160–226	12–16	29–40	87–95
7	South Savo	30,079	59	3.9	67	0.7–1.4	286–588	0.4–0.5	1–2	87–92
8	North Savo	56,774	145	8.5	59	3.6–5.1	188–358	11–12	23–27	83–91
9	North Karelia	28,949	78	4.7	60	1.9–2.8	192–360	5–6	23–27	81–91
10	Central Finland	32,974	85	4.9	57	2.1–3.1	175–312	8	27–31	79–91
11	South Ostrobothnia	100,700	230	13.8	60	5.2–7.8	172–305	16–19	19–24	79–84
12	Ostrobothnia	65,802	159	9.9	62	4.0–5.2	181–327	9–11	16–19	85–89
13	North Ostrobothnia	45,562	191	11.9	62	3.2–5.4	221–441	3–4	9–10	83–89
14	Kainuu	8317	21	1.2	56	0.3–0.6	208–414	0.7–0.8	9–13	82–91
15	Lapland	8457	32	1.9	59	0.5–0.8	217–431	0.3–0.4	4–6	87–88
16	Åland	6614	14	0.8	62	0.4–0.5	183–341	0.7–1	12–18	88–92
	Sum	782,667	2070	128		77–86		211–259		

* STD <0.01; ** STD ≤0.1.

4. Discussion

4.1. Soil OC stock in the uppermost 15 cm in mineral agricultural soils

Estimated municipality specific soil OC stocks varying from 40 to 81 Mg C ha^{-1} were slightly higher but well in line with the OC stocks observed in national soil monitoring reported by Heikkinen et al. (2013). In national soil monitoring, the average OC stocks in arable mineral soils were found to range between 41 and 67 Mg C ha^{-1} in the first 15 cm depending on the region and soil type (Heikkinen et al., 2013). Here, the BD was calculated the same way as in Heikkinen et al. (2013), and the slightly higher OC stocks found in the present study are

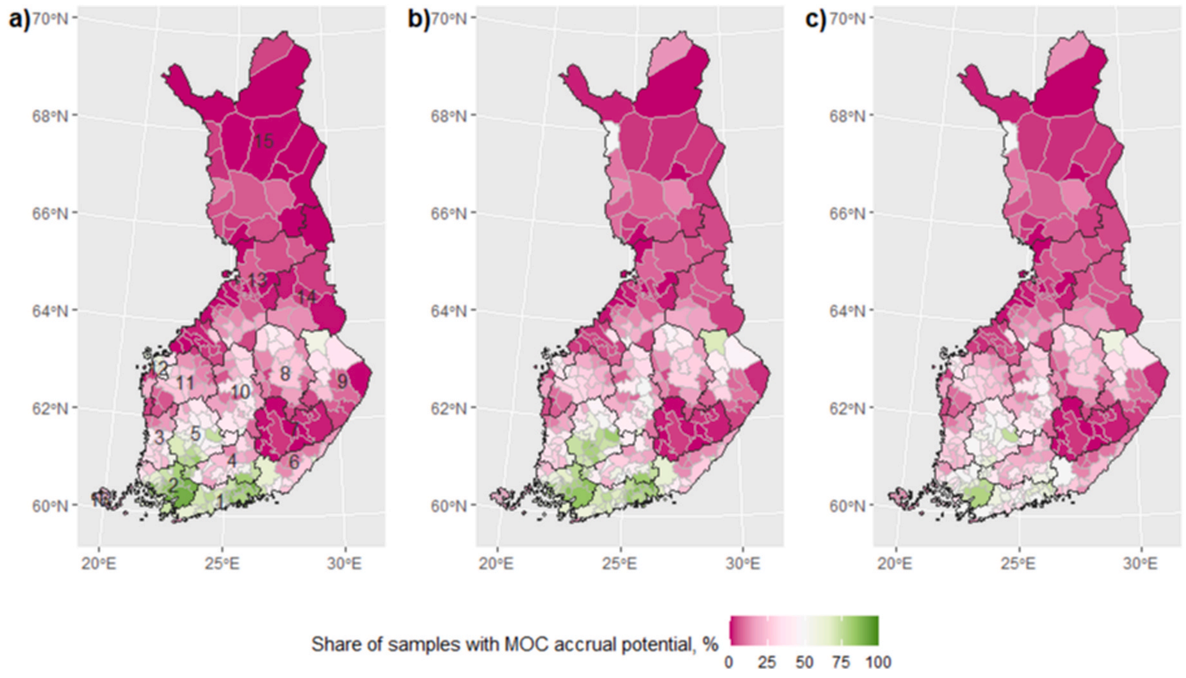

Fig. 6. Share of samples (%) in each municipality with an OC saturation degree of less than 100%. The saturation degree was calculated by dividing the prevailing OC stock in the uppermost 15 cm soil layer (SOC_{15cm}) by the maximum capacity of soil mineral matter (clay or clay + silt) to protect OC (MOC_{15cm}) estimated based on a) soil clay content according to Dexter et al. (2008) and fines (clay + silt) content according to b) Schjønning et al. (2012) and c) Hassink (1997). The numbers refer to regions (black borders) listed in Table 2.

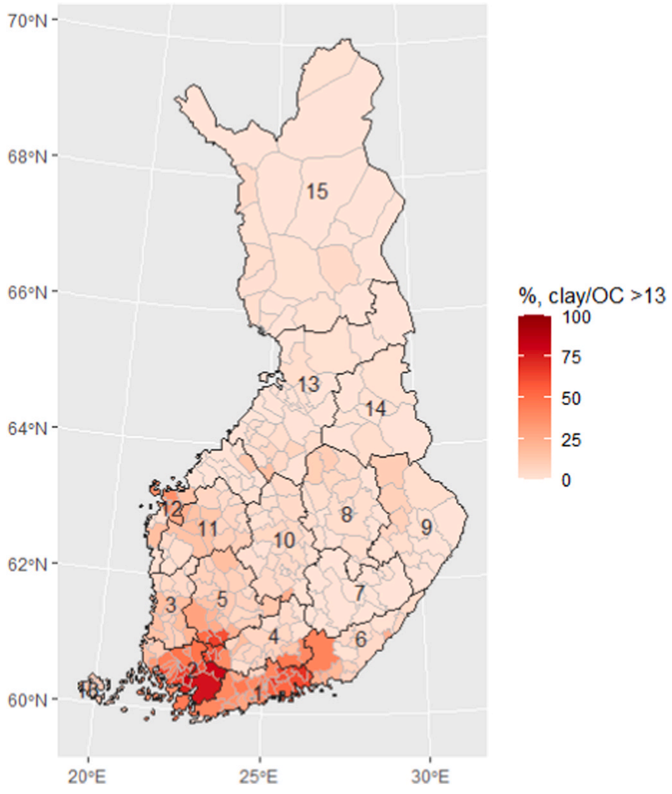

Fig. 7. Share of samples with a clay/OC ratio higher than 13 and therefore having a high risk of structural instability in each municipality in Finland. The numbers refer to regions (black borders) listed in Table 2.

therefore the result of the higher OC content estimates (g kg^{-1}). The OC stock estimations were based on the ST data in which the samples are classified in four OM classes. We utilized actual measured OC contents from NSM data, complemented with other data sources, to establish the distribution within each OM class. This information was then used to adjust the OC content estimations (finger assessment) for the ST data. When combined with the OC content distribution within OM classes extracted from measured OC data, the OM classes can be used to approximate the OC content of the field parcel. The small standard deviations of the OC stocks reflect the fact that although there is variation in OC content within the OM classes around the median in the smaller data set including NSM data, the distributions of the OC contents within OM classes are not normal, and most of the observations are therefore very close to the median. However, this calculation method does not take the error originating from the sample to be wrongly classified during the ST finger analysis into account, in other words, the possibility of a sample being placed in an OM class that does not match its true OC content.

Observed OC stocks in the uppermost 15 cm of mineral agricultural soils are high compared with those in central and southern Europe. For example, average stocks of agricultural land in the 0–30 cm soil layer have been reported to be an average of 50 Mg C ha^{-1} in Belgium (Meersmans et al., 2011) and 51 Mg C ha^{-1} in Italy (Chiti et al., 2012). The OC stock has been shown to increase towards high latitudes (Crowther et al., 2019). Taking the differences in sampling and in how the OC content is measured or estimated in NSM and ST data sets, respectively, into account, the nationwide OC stock of 128 Tg in the 0–15 cm soil layer estimated in the present study is of the same magnitude as in the previous study by Heikkinen et al. (2013), which reported a total OC stock of 117 Tg for agricultural mineral soils based on NSM data.

4.2. *Climate change mitigation potential*

The potential to increase mineral-protected OC in the uppermost 15 cm of mineral agricultural soils in Finland was estimated to range

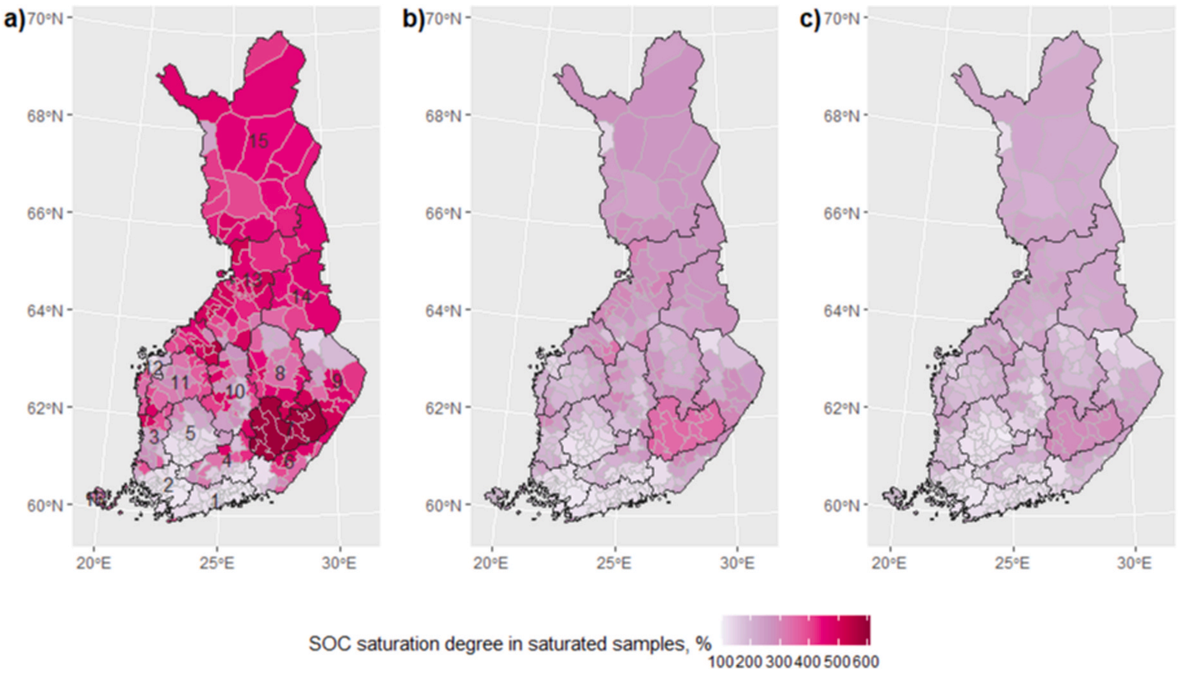

Fig. 8. Median OC saturation degree (%) in saturated soil samples in each municipality. Saturation degree was calculated by dividing the prevailing carbon stock in the uppermost 15 cm (SOC_{15cm}) by the maximum capacity of soil mineral matter (clay or clay + silt) to store/protect OC (MOC_{15cm}) estimated based on a) soil clay content according to Dexter et al. (2008) and fines (clay + silt) content according to b) Schjønning et al. (2012) and c) Hassink (1997). The numbers refer to regions (black borders) listed in Table 2.

between 0.21 and 0.26 Tg and the field area estimated based on the number of the unsaturated samples with potential to contribute to OC sequestration was 32–40% of the total area of mineral agricultural soils. According to the applied calculation methods, the majority of surface soil samples in Finland are therefore OC saturated. Even among the OC deficit samples with potential to build up stable OC, OC saturation was relatively high, being mostly over 80% among the municipalities and regions. In contrast, Chen et al. (2018) reported most of the cropland soils in France to be carbon deficient with mean OC saturation degree of 36% in uppermost of 30 cm. Similarly, Wiesmeier et al. (2014) reported mean OC saturation of 47% in uppermost 0–10 cm in the croplands of southern Germany. Additional OC inputs are stored to a lesser extent in a stable form of OM as the soil approaches its OC saturation (Chenu et al., 2019; Stewart et al., 2007). Hence, in contrast to temperate soils, which are considered largely unsaturated and therefore to have technical potential to build up stable mineral-protected OC (Georgiou et al., 2022; Zomer et al., 2017; Wiesmeier et al., 2014), the additional contribution of the uppermost mineral agricultural soil layer in Finland to climate change mitigation through OC accrual is relatively small.

The aggregate potential for OC accrual in mineral protected form (0.21–0.26 Tg) represents only 0.2% of the current OC stock in the 0–15 cm layer (128 Tg). This potential to increase mineral-protected carbon storage in mineral agricultural fields in Finland corresponds to 0.7–0.9 Mt CO_2 eq. in total. In comparison, annual carbon sequestration in Finnish mineral forest soils has been estimated to vary between 5 and 10 Mt CO_2 eq. between 1990–2015 (Lehtonen et al., 2019). In 2021, the net Finnish GHG emissions totalled 48,3 Mt CO2 eq. (Official Statistics of Finland, 2023). In the national context, the overall potential of the managed uppermost layer in mineral agricultural soils to sequester OC in stable mineral-protected form is equivalent to GHG emissions of only six days. On the other hand, mineral agricultural land represents a significant carbon storage: the current total OC stock and the estimated stock of OC not protected by mineral matter in saturated areas in the top 15 cm layer corresponds to c. 9 and 3 times, respectively, of the year 2021 GHG emissions in Finland. Currently, arable mineral soils in Finland are losing OC at the rate of 0.4% $year^{-1}$ on average (Heikkinen et al., 2013). Mitigating the current OC loss (0.4% annual loss) equates to 0.51 Tg OC annually, highlighting the importance of implementing actions to maintain OC stocks in Finnish mineral soil. According to Heikkinen et al. (2022), high-OC soils are prone to high OC losses, whereas in fields with a long cultivation history (>100 years), the changes in OC content have levelled off, and the ratios of OC to fine-sized particles tend to be fairly similar.

Finland is committed to the 4 per 1000 initiative which was started in 2015 at the Paris United Nations Climate Change Conference, COP21, with an objective of increasing soil carbon sinks by 0.4% a year globally. The possibility of achieving this objective in Finland has been studied by modeling crop residue and manure inputs and objective was not fulfilled even with a 20% increase in organic input (Tao et al., 2023). As our results show that the most stable OC pool is nearly saturated, contributing to the 4 per 1000 initiative would require a focus on increasing the OC pool with higher amounts of plant material, which might also be of higher recalcitrance (Angst et al., 2023), or with biochar, which is a highly recalcitrant form of carbon and can be used to increase OC stocks, even in saturated soils.

Our estimate of the potential of mineral agricultural soils to contribute to climate change mitigation includes only the uppermost 0–15 cm soil layer. For soil testing, farmers are advised to sample the soil down to the depth of the plough/tillage layer, and the ST data does not therefore represent the soil below the plough layer. Further, estimation down to 15 cm enabled a comparison with the national OC stock estimate of Heikkinen et al. (2013) based on NSM data. However, it is noteworthy that the uppermost 15 cm soil layer reported here represents only a fraction of the total soil OC stock (Palosuo et al., 2015, Supplement). According to the NSM data, there is a steep gradient in OC content in the uppermost 40 cm of soil (Heikkinen et al., 2021), also evidenced in boreal conditions by Etana et al. (1999), Soinne et al. (2020), and Salonen et al. (2023), thus suggesting OC deficiency below the plough layer. Based on the OC saturation theory, although there is large additional OC accrual potential in deeper soil layers (Chen et al., 2018), it may be difficult to realize the potential in field conditions. Recent research has shown that only a limited amount of OC can enter the subsoil (Liebmann et al., 2020, 2022; Heikkinen et al., 2022; Menichetti et al., 2015; Salonen et al., 2023) and the potential of subsoil to accrue MOC should therefore not be estimated based on soil texture only since other biogeochemical constraints may prevent OC stabilization in subsoil (Salonen et al., 2023). The highest potential for OC accrual likely is below the managed surface layer, between 15 and 40 cm, where the conditions are likely to be favorable for increased OC accumulation, provided that soil structure allows root growth and DOC leaching and supports biological activity that contributes to translocation of OC from the upper soil layers (Rumpel and Kögel-Knabner, 2011). However, it is clear that more information about the potential to sequester OC in relatively stable form below the managed surface soil in different climates and soil types is needed (Skadell et al., 2023).

4.3. Applicability of the MOC_{Max} calculation methods

When the MOC_{Max} is calculated based on the content of fine-sized particles using Hassink's equation, the maximum OC content that any soil can hold in mineral protected form is 41 g kg^{-1} (share of <20 µm particles = 100%). If a 15% share of POC (Angers et al., 2011) is assumed, the soil would be saturated at a 48 g kg^{-1} content of total soil OC. This is fairly similar to the number which results when the MOC_{Max} for the same soil with a 100% share of fine-sized particles (<20 µm) is estimated in accordance with Schjønning et al. (2012). According to Schjønning et al. (2012), OC saturation is reached at a fines/OC ratio of 20, and saturation would therefore be reached at 50 g C kg^{-1}. Indeed, Cotrufo et al. (2019) suggested this 50 g C kg^{-1} to be the flex point at which MOC_{Max} was reached and further increase in soil OC would build up only the POC fraction. However, Begill et al. (2023) did not find any support for the upper limit of MOC content in relation to total soil OC. Higher MOC_{Max} estimates than the suggested flex point of Cotrufo et al. (2019) will result when the estimation is based on clay-sized particles, as in Dexter's equation. Following the theory of Dexter et al. (2008) leads all soils with clay content higher than 50% to exceed the flex point suggested by Cotrufo et al. (2019) and the MOC protective capacity estimated based on fine-sized particles (<20 µm) according to Hassink's and Schjønning's methods. Dexter's theory is supported by the MOC content larger than 55 g kg^{-1} reported by Salonen et al. (2023) for heavy clay soil with 68% clay content and larger than 60 g kg^{-1} OC. For high-clay soils, the MOC_{Max} will therefore probably be underestimated if the estimation is based on the content of fine-sized particles (<20 µm) in the soil. On the other hand, disregarding the capacity of fine-sized particles to protect OC will probably lead to an underestimation of the protective capacity of coarser textured soils.

In France, the OC sequestration potential and OC storage potential have been estimated based on Hassink's equation and a data-driven approach using the French National Soil Monitoring Network in delineating carbon-landscape zones for arable soils (Chen et al., 2018, 2019). Both approaches, though relying on different concepts, resulted in fairly similar outcomes, except in high-clay mountain areas, where the data driven approach offered a lower potential for OC storage (Chen et al., 2019). Chen et al. (2019) concluded, that achieving the theoretical OC sequestration potential might be challenging in arable high-clay soils.

In Finnish mineral soils, a large share of mineral particles in clay-size fraction are actually quartz particles (Keskinen et al., 2022) with very low reactivity, suggesting that the estimations of MOC_{Max} based on equations calibrated in different soil types and climate may overestimate the protective capacity of mineral particles in cool and humid areas with relatively young soils. However, in slightly acidic soils in humid areas, the oxalate extractable aluminum (Al) and iron (Fe) considered to represent poorly crystalline oxides have been found to be tightly linked to OC content indicating Al and Fe play an important role in OC stabilization (Fukumasu et al., 2021; Rasmussen et al., 2018). The oxalate extractable Al and Fe can contribute to OC stabilization by enhancing sorption onto oxide surfaces (Kaiser and Guggenberger, 2000) or the complexation and coprecipitation of organo-metal complexes (Wagai and Mayer, 2007).

High OC saturation degrees or oversaturation have been reported in coarse textured soils (Wiesmeier et al., 2014; Angers et al., 2011; Carter et al., 2003) located in high latitudes with a cooler climate (Angers et al., 2011) or with a relatively low pH (Wiesmeier et al., 2014). These findings suggest that the mechanisms of OC protection might differ in coarser and acidic soils (Rasmussen et al., 2018; Kleber et al., 2005) compared to fine textured soils. Consequently, the content of fine-sized particles may not be optimal for predicting the maximum capacity to protect OC in coarser mineral soils. The clay/OC and fines/OC ratios were developed in the context of soil structure and presented in relation to the risk of colloid dispersion (Schjønning et al., 2012; Dexter et al., 2008) whereas in coarse soils, OC is more important for enhancing water retention and cation exchange capacity than in high-clay soils. Therefore, when considering soil functioning and productivity, the clay/OC ratio threshold values developed in the context of soil structure may not include relevant information for evaluating the state of coarse soils.

The general applicability of the equations for predicting the MOC_{Max} based on soil texture alone can therefore be questioned in the light of mineralogical differences and differing OC stabilizing mechanisms not directly related to texture. In addition, the multilayer arrangements of organic molecules detected in patches on mineral surfaces (Schweizer, 2022) suggest that MOC_{Max} estimates based on particle size distribution—largely defining mineral surface area—may be too simplistic (Schweizer et al., 2021). However, Schweizer et al. (2019) suggested that the role soil texture plays in OC stabilization is largely indirect occurring through the distribution of OM in different aggregate fractions. This indicates that clay-sized particles, which drive the aggregation process, play a central role in defining the OC protective capacity in soil.

4.4. Implications for managing mineral agricultural soils in changing climate

Soil carbon stocks are expected to accumulate with the adoption of carbon farming practices (Lal, 2004) or the complete abandonment of agricultural soils altogether (Vuichard et al., 2008). The promoted practices impact the soil by increasing the input of organic material and preventing soil disturbance (Lal, 2004). Using carbon farming practices is estimated to increase global cropland OC stock by 400–800 Tg C annually via conservation tillage (100–1000 kg ha^{-1} yr^{-1}), cover crops (50–250 kg ha^{-1} yr^{-1}), diversified cropping systems (50–250 kg ha^{-1} yr^{-1}), and manure and nutrient management (50–150 kg ha^{-1} yr^{-1}), among others (not additive values) (Lal, 2004). However, the OC accrual outcomes of the different practices are affected by initial OC content and soil texture. For example, high initial OC has been linked to decreasing OC trends, whereas soils with low initial OC content are more likely to have increasing OC trends (Henryson et al., 2022; Riley et al., 2022; Hanegraaf et al., 2009; Bellamy et al., 2005). Furthermore, Gubler et al. (2019) found that it was the initial ratio of clay/OC rather than the initial OC content which determined the OC trends, highlighting the importance of considering OC content in relation to soil texture. According to Gubler et al. (2019), soils with high clay/OC ratios have a high potential to increase OC.

According to Soinne et al. (2021), in fine-textured soils, the higher the clay content, the more OC is needed for high productivity, suggesting a potential for improved productivity in high-clay soils with increasing OC content. Similarly, according to Dexter et al. (2008) and Schjønning et al. (2012), soil structural stability is better in soils with low clay/OC or fines/OC ratios, and the OC deficit areas defined using Dexter et al. (2008) and Schjønning's (2012) equations therefore also indicate areas where soil functioning could be improved with OC accrual. Despite the relatively large OC stocks in the mineral arable soils of Southwest-Finland, the clay/OC ratios were mostly higher than 13, a threshold value suggested for degraded soil (Prout et al., 2021; Johannes et al., 2017). Southwest-Finland is also identified as an area with high-risk for erosion (Räsänen et al., 2023), contributing to particulate phosphorus load and the eutrophication of the Baltic Sea. Aims to increase OC content could therefore also contribute to a reduction of nutrient losses to surface waters through improved aggregate stability and reduced clay dispersion (Soinne et al., 2016; Dexter et al., 2008). Guillaume et al. (2022) suggested prioritization of the application of organic amendments in the least saturated croplands (<65%), which could be the most effective strategy to contribute to climate change mitigation and adaptation (Guillaume et al., 2022). However, OC accrual targets should be related to local soil management options (Amelung et al., 2020) and to the regional availability of organic amendments and side streams suitable as organic soil amendments. The results of the present study suggest that the selection of sites with the most potential for additional long-lasting carbon storage could be done on a parcel-scale by utilizing the agronomic ST data.

Alongside the aim of increasing OC accrual in mineral agricultural soils, we should stress the importance of maintaining the current OC stocks, especially in high-OC soils. Especially in Eastern and Northern Finland, the theoretical capacity of mineral surfaces to stabilize OC is considerably exceeded. In oversaturated soils, positive OC accrual is unlikely (Georgiou et al., 2022), which means that rather than aiming to increase the OC storage in soils high in OC, these soils call for management options that maintain the existing high OC levels and reduce OM mineralization. Although inputs of highly recalcitrant organic materials like biochar could help in increasing total OC mainly by increasing the POC in saturated and high-OC soils (Angst et al., 2023), to ensure the net removal of carbon from the atmosphere, the application of biochar in agricultural soils should be considered in the light of soil productivity and the availability of biomasses for biochar production. Biochar, when applied with a consideration of yields, ecosystems, and ecosystem conservation, could theoretically deposit 490 Tg C annually on the Earth's soils (Woolf et al., 2010). Biochar has a relatively high positive yield impact in the tropics supporting its use as a means of OC sequestration, but positive yield impacts are currently less likely in temperate regions (Jeffery et al., 2017) or in the boreal zone, (Soinne et al., 2020; Kalu et al., 2021). In addition to biochar, processing organic wastes by composting or anaerobic digestion could create opportunities to increase or maintain soil OC content (Chavez-Rico et al., 2022). Developing the manufacturing methodologies of organo-mineral fertilizers, a relatively new category of fertilizer products, to provide fertilizers rich in relatively stable organic matter could further support the circular economy (Bouhia et al., 2022).

A modelling study on global OC data indicated that agricultural land-use has substantially reduced OC following the reclamation of land for agriculture (Sanderman et al., 2017), and in Finnish conditions soil monitoring has indicated that such a change is ongoing (Heikkinen et al., 2013, 2022). A plausible explanation of the latter is that a considerable part of the Finnish field area has been reclaimed for agriculture in the last century, meaning it is likely that these cultivated soils have yet to reach a new steady state (Heikkinen et al., 2013). It has been suggested that carbon loss due to land use change primarily originates from the POC fraction, which is more vulnerable to environmental changes than the MOC fraction (Heckman et al., 2022; Lugato et al., 2021; Rocci et al., 2021). According to a global study by Rocci et al. (2021), the average change in POC is three times greater than that in MOC due to the warming climate. The adoption of soil OC-preserving management practices in oversaturated soils is important, especially as OC loss in the conversion from natural land use to cropland occurs in a shorter time scale than the accrual of soil OC in the reverse process (Or et al., 2021). Furthermore, given the stabilization processes and role in soil functioning, the sufficient or optimal OC level in coarse soils in cool and humid climate needs further research.

It is clear that preserving the vast carbon storage in mineral agricultural soils is of crucial importance in Finland. Although the potential to sequester additional OC in mineral protected form was found to be small, aiming to increase the OC stock of the unsaturated soils has potential to improve soil functioning and productivity. Specific climate and soil conditions should be taken into account in management practices aimed at preserving carbon storage or enhancing carbon accrual. Furthermore, more information is needed on the costs of different carbon farming practices in Finnish conditions taking into account the crop yield or fertilizer savings. Increasing soil OC content, as well as maintaining current stocks and even reducing the current rate of OC loss, could be a source of income for farmers alongside the other commodities that the agricultural sector produces; however, subsidies or market-based economic incentives may still be required (Lal, 2020).

5. Conclusions

The results of the study address the high OC reserves in the uppermost 15 cm in Finnish mineral agricultural soils. Results also suggest that the potential of the managed uppermost layer to contribute to climate change mitigation by stabilizing OC onto mineral surfaces is relatively low. When estimated based on soil texture, the coarser soils of the eastern and northern parts of Finland are largely saturated, and as the protective capacity of mineral particles is exceeded, OC is likely to exist in a form more vulnerable to climate warming. In these areas, rather than trying to extensively increase carbon capture, we should therefore stress the importance of maintaining the current high OC stocks and managing the soils accordingly. Regarding soils with large OC stocks and oversaturated soils, the risk of climate change -induced enhanced mineralization of organic matter should be taken into account. However, more information about OC stabilization mechanisms and maximum MOC protective capacity in coarse textured soils is needed. OC deficient soils showing potential for mineral-protected OC accrual are located in Southwest Finland's intensively cultivated areas, which typically have a high clay content. These high-clay soils would potentially also benefit from additional OM through improved soil structure and productivity.

CRediT authorship contribution statement

Helena Soinne: Conceptualization, Data curation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Matti Hyyrynen:** Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Medilė Jokubė:** Writing – original draft, Writing – review & editing. **Riikka Keskinen:** Conceptualization, Writing – original draft, Writing – review & editing. **Jari Hyväluoma:** Methodology, Writing – original draft, Writing – review & editing. **Sampo Pihlainen:** Writing – original draft, Writing – review & editing. **Kari Hyytiäinen:** Writing – original draft, Writing – review & editing. **Arttu Miettinen:** Methodology, Writing – original draft, Writing – review & editing. **Kimmo Rasa:** Conceptualization, Writing – review & editing. **Riitta Lemola:** Data curation, Writing – review & editing. **Eetu Virtanen:** Writing – review & editing. **Jussi Heinonsalo:** Writing – review & editing. **Jaakko Heikkinen:** Conceptualization, Data curation, Methodology, Writing – original draft, 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.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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