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Assessing the effect of arable management practices on carbon storage and fractions after 24 years in boreal conditions of Finland

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A B S T R A C T

Soil organic matter (SOM) plays an important role in soil functions that are crucial for sustainable agriculture. Understanding how agricultural management and soil properties affect SOM in different soil depths would aid in maintaining and increasing SOM throughout the soil profile. We sampled a 24 year-old cultivation field experiment with organic and conventional cropping systems, and an adjacent unmanaged meadow to 70 cm soil depth to assess the total organic carbon (OC) stocks and the distribution of OC into mineral-associated (MAOM), particulate (POM) and dissolved (DOM) organic matter. We found that >83% of the soil OC was in the MAOM fraction, and that the distribution of OC across the MAOM, POM and DOM within a soil depth was not strongly affected by soil management. Largest OC stocks (169 t ha^{-1}) together with the largest plant root biomass was found in the unmanaged meadow, which highlights the potential of deep-rooting plants in sequestering OC into the soil. The OC saturation state of the soil was assessed based on the clay to OC ratio and Hassink's Equation (Hassink 1997). Hassink's Equation seemed to underestimate the MAOM accrual capacity of these soils and thus overestimated soil OC saturation state, whereas the clay to OC ratio indicated potential for OC accrual in all soil depths except for the meadow topsoil. These varying results suggest that the applied metric should be soil type and -depth specific. We also determined the contribution of clay content and aluminum and iron oxides in explaining the amount of total OC, MAOM-C and POM-C. In contrast to the aluminum and iron oxides, clay was not well correlated to any of the OC fractions below the 20 cm depth, suggesting that estimating the OC accrual potential of the deeper soil should not be based on the soil texture alone. Our results indicate that aluminum and iron oxides can play an important role in transporting and stabilizing of OC in the soil profile.

1. Introduction

Current agricultural management has led to a decline in global carbon (C) stocks in soil organic matter (SOM) in topsoils (0–30 cm) by 26%, and in the deeper soil profile (0–100 cm) by 16% (Sanderman et al., 2017), and a continuing annual decrease of arable soil organic carbon has been reported in Finland (Heikkinen et al., 2013). The SOM loss threatens the viability of agriculture as it is essential in a multitude of soil functions such as; primary productivity, carbon sequestration and climate regulation, water purification and regulation, providing habitat for biodiversity, and in the recycling of nutrients (e.g., Schulte et al., 2014; Wiesmeier et al., 2019; Hoffland et al., 2020). The management-derived depletion of SOM also contributes to climate change by increasing atmospheric carbon dioxide (CO_2) concentrations (Paustian et al., 2016). To prevent further SOM reduction and to mitigate climate change it is important to learn how soil properties and agricultural management affect the form of soil organic carbon (OC) and the size of OC stocks across different soil depths.

To determine the form of soil C, SOM can be physically divided into two fractions (Tiessen and Stewart, 1983; Cambardella and Elliott,

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1992; Lavallee et al., 2020): to relatively stable mineral associated (MAOM), and to more labile particulate (POM) organic matter. MAOM is presumably mainly of microbial origin (Cotrufo et al., 2013; Kallenbach et al., 2016) but some portion of it derives from leached plant material (Angst et al., 2021; Yu et al., 2022), whereas POM consists of relatively intact plant material (Lavallee et al., 2020). MAOM is stabilised by its interactions with soil minerals while POM has only limited interaction with minerals, although soil aggregation or the soil physicochemical status may hinder its decomposition (Lavallee et al., 2020). In addition to MAOM and POM fractions, a minor part of the soil organic carbon can be extracted from the soil as dissolved organic matter (DOM) (Kalbitz et al., 2000; Von Lützow et al., 2007).

In arable mineral soils, largest part of the OC stock is in the MAOM (Kögel-Knabner et al., 2008; Georgiou et al., 2022). Various aspects regulate the total amount of SOM and its distribution to the different OC forms (MAOM-C, POM-C and DOM-C). Soil properties, such as texture and amount of aluminum (Al) and iron (Fe) oxides control on their part the size of the soil OC stock in MAOM (Von Lützow et al., 2007). The amount of clay (< 2 μm) sized particles has traditionally been considered as an adequate predictor for a maximum capacity of the mineral-associated soil OC stock (Dexter et al., 2008) as the proportion of these particles gives a reference of mineral surface area available for MAOM binding (Wiesmeier et al., 2019). Hence, combining soil clay content with soil OC content (i.e., clay to OC ratio) could serve as a sensible metric for assessing OC deficit or OC accrual potential of a given soil (Dexter et al., 2008; Schjønning et al., 2012; Prout et al., 2021).

Soil properties, such as the contents of clay and Al and Fe oxides, derive primarily from the weathering of the soil parent material, in combination with environmental conditions, such as precipitation and temperature (Jenny, 1941). The weathering capacity of parent material is therefore dependent on the regional climatic conditions. This context specificity in terms of climatic region is critically important when understanding the underlying mechanisms for carbon sequestration and may require that clay content alone is not considered as the most suitable predictor of MAOM-C storage capacity. Al and Fe oxides act efficiently as OC binding agents (Wiseman and Püttmann, 2006; Wiesmeier et al., 2019; Mendez et al., 2020; Hall and Thompson, 2022), and in humid cold climates with relatively low pH, such as the Boreal conditions in Finland (Metzger et al., 2012), their oxalate-extractable species have been shown to be better predictors for the soil OC than soil texture alone (Rasmussen et al., 2018; Wiesmeier et al., 2019; Fukumasu et al., 2021). In humid Boreal climate periodic water saturated conditions may have two-way effects on the SOM dynamics: waterlogging is likely to hinder the decomposition of POM due to microbial inhibition (Lugato et al., 2021). On the other hand, water saturation may cause Fe to reduce, potentially releasing MAOM-C from mineral complexes (Huang and Hall, 2017).

In addition to soil properties, agricultural management is an important regulator of OC storage capacity in arable soils (e.g., Tiefenbacher et al., 2021). Examples of the management practices that can be applied to aid increasing soil carbon storage are reduced tillage (Smith et al., 2008), cultivation of deep rooting plants (Thorup-Kristensen et al., 2020), and the use of organic fertilizers, such as manure (Maillard and Angers, 2014). However, as the outcome of these procedures is highly context-dependent, it is challenging to make universally applicable generalizations on their effects on soil OC stocks. In addition, as most soil carbon studies only consider the top layer of ca. 30 cm of arable soils (Yost and Hartemink, 2020), there is less knowledge on the impact of these practices on the whole soil profile OC stock. For example, the effect that deep-rooting plants have on soil OC is not unambiguous. Deep-rooting grassland plants can allocate as much as 60% of photosynthesised OC belowground (Jackson et al., 2017) which could potentially increase soil OC stocks. However, root exudates may also have opposite effects: they may cause MAOM desorption from mineral surfaces (Keiluweit et al., 2015), as well as increase soil microbial activity which leads to MAOM-C mineralization (so called priming effect; Kuzyakov et al., 2000). Likewise, effects of tillage can be contrasting in different soil depths (Haddaway et al., 2016; Ogle et al., 2019; Cai et al., 2022). Disturbance caused by tillage may hasten SOM mineralization in the topsoil (through increased aeration and disturbance of aggregates, Grandy and Robertson, 2007) but concurrently, may translocate SOM into the deeper soil depths which may guard it against decomposition by soil organisms (Button et al., 2022).

There are several potential stabilisation mechanisms for SOM below the plough layer. In general, lower temperatures and periodical anoxic conditions may hinder SOM mineralization (Button et al., 2022). As in the topsoil, soil properties may promote the formation of organo-mineral association with clay-sized soil minerals and binding to Al and Fe oxides. There is estimated to be considerable potential for increasing subsoil OC storage, as globally it is approximated that only 21% of the subsoil (below 30 cm) MAOM storage capacity is currently occupied (Georgiou et al., 2022). As the mechanisms behind SOM stabilisation and its distribution to different fractions may vary with the soil depth, assessing predictors and potential metrics for the total amount of OC and stabilised OC (i.e., MAOM-C) in different soil depths could support the attempts to increase deep soil OC stocks for climate mitigation (Dynarski et al., 2020).

We explored the effects of organic and conventional crop rotations on soil OC stocks down to the depth of 70 cm, and on the distribution of OC into different SOM fractions (MAOM, POM and DOM) in a Finnish long-term field experiment (established in 1995). We hypothesized that the organic crop rotation system receiving organic fertilization (manure) would have higher carbon stock when compared to the conventional crop rotation receiving mineral fertilization only. The results from the cropping systems were compared to an adjacent permanent meadow that was assumed to have the highest OC stock and to be closest to the OC saturation due to deep-rooting plants and high litter- and root-derived OC inputs. The unmanaged meadow was representing an undisturbed soil and maximum OC input without external SOM additions and expected to reveal the practical OC accrual potential of soil in relation to soil properties (i.e., clay content and Al- and Fe oxides). We anticipated the MAOM-C levels to be positively correlated with clay, Al and Fe oxides in the topsoil of all the studied soils. As OC levels are assumed to drop with increasing soil depth, below 30 cm depth MAOM-C was expected to correlate with Al and Fe oxides only as they are supposedly preferential binding sites for the OC.

2. Material and methods

2.1. Study site and soil sampling

Soil samples were taken in October 2019 from Yöni field experiment (Natural Resources Institute Finland) in Jokioinen, South-Western Finland (60°51′44.5"N 23°31′24.5″E). Parent material of the soil is glaciofluvial clay (Yli-Halla et al., 2009) and the field is classified as a Vertic Stagnosol (IUSS Working Group WRB, 2015; Yli-Halla et al., 2000). Mean annual precipitation is 600 mm and temperature 5 °C. Artificial drainage was installed in the field at the depth of 1 m in 1989.

The field experiment was established in 1995 on a site that had been extensively managed grassland since the beginning of the 20th century. Cultivation in some parts of the field started in 1990 and between 1990 and 1995, the crop rotations differed slightly from the fixed crop rotation system which was established in 1995 in the whole experimental area (Table 1). In 1990, soil samples for soil fertility assessment (composite samples from c. 0–25 cm) were collected from the field. In the plots where unmanaged meadow, and organic and conventional crop rotations were later established OC contents (g kg^{-1}; ±SE) were: 52 ± 7.1, 50 ± 3.0, and 53 ± 2.2, respectively. At the time of establishing the experiment (year 1995), part of the field was left to develop as a natural, unmanaged meadow. The unmanaged meadow closely resembles to a grassland by its vegetation but is not used as a pasture. No management procedures were performed for the unmanaged meadow, except for

Table 1
Cultivated plants of the five-year crop rotation in the Yöni field. The rotation has been similar since 1995 excluding some exceptions*: in cases when the winter rye was not wintering well, oat was sown in the spring. In the organic plots, occasional years of bare fallow were utilized to assist in weed management.

Yöni crop rotation, since 1995	
Year 1	Spring barley (*Hordeum vulgare* L.) and perennial grass mixture of timothy (*Phleum pratense* L.), meadow fescue (*Festuca pratensis* (Huds.) P. Beauv.) and red clover (*Trifolium pratense* L.)
Year 2	A perennial grass mixture of timothy, meadow fescue and red clover
Year 3	A perennial grass mixture of timothy, meadow fescue and red clover, with winter rye (*Secale cereale* L.) seeds sown in autumn
Year 4	Winter rye
Year 5	A mixture of oat (*Avena sativa* L.) and pea (*Pisum sativum* L.)

* Exceptions in crop rotation: 2012, plot 10 (org.) was fallow; in 2013, plot 5 (conv.), and plot 6 (org.) cultivated with oat; in 2015, plot 13 (org.) was fallow; in 2016, plot 9 (org.), and 10 (conv.) cultivated with oat; in 2017, plot 10 (org.) was fallow.

removal of trees if they appeared. The remainder of the field had two cultivation systems: 1) organically and 2) minerally fertilized cereal crop rotations in three randomized blocks. Plot size was approximately 150 × 20 m. Both systems had the same cultivated plants in a five-year rotation since the start of the experiment (Table 1) and similar ploughing; during each five-year crop rotation, soil was ploughed three times to 20 cm depth. Equal amount of harvest residues was left in the organic and conventional systems. The conventional system was minerally fertilized according to the nitrogen and phosphorus fertilization limits of the prevailing Agri-Environmental Programme and herbicides (glyphosate and MCPA) were applied approximately six times per five-year crop rotation cycle. In the organic system, cattle manure was applied as the form of fertilizer and no herbicides were used. During the five-year crop rotation, the organic system received the amount of manure containing total N excreted by a 0.5 dairy cow (50 kg ha^{-1} y^{-1}). The amount was based on the sufficiency of achieved yield levels before 1995 to meet a fodder requirement of 0.5 dairy cows. The amount of phosphorus in the applied manure was determined by the nitrogen-adjusted manure application rate. From the start of the field experiment to the time of our soil sampling, average yearly nutrient amounts that the cropping systems received in the fertilization were: 26 kg ha^{-1} phosphorus and 95 kg ha^{-1} nitrogen for the conventional system, and 10 kg ha^{-1} phosphorus and 50 kg ha^{-1} nitrogen for the organic system. In the conventional system, all the fertilizer nitrogen was in a soluble form, and in the organic system 43% (22 kg y^{-1}). There were no OC inputs to the conventional system. As the OC content of the manure used as organic fertilizer was not analysed, the yearly OC inputs to the organic cropping system were estimated based on literature (Ylivainio et al., 2019; Saastamoinen et al., 2022) to be 0.62–0.73 t OC ha^{-1}, adding up to 14.9–17.4 t OC ha^{-1} in total during the 24-year duration of the field experiment. Experimental plots have not been limed regularly. Some of the plots were limed 14 years prior to our sampling but judged by the low variation in measured pH (Table 2) across the managements and soil depths, the possible effects from liming have faded before our soil sampling.

In each of the cultivated plots, three one-meter-deep soil cores were collected (i.e., 9 soil cores per soil management) such that the distance from the outer edges of the plot were 10 and 6 m, and the inter-sample distance was approximately 12 m. Sampling was performed with the technique presented in Persson and Bergström (1991) and Uusitalo et al. (2012). In short, one-meter-long PVC – tubes (inner diameter 6.8 cm, outer wall of the tube 3 mm) were screwed into the soil and then pulled out. The adjacent permanent meadow, which was not a part of the complete randomized block design, was divided into three plots, sized approximately 50 × 20 m each, and sampled in the same way as the cultivated fields.

Table 2
Soil pH, electric conductivity (EC, 0.1mS/cm), and Al and Fe oxides (g kg^{-1}) in three management systems (conventional, organic and meadow) per soil depth (±SE, $n = 3$).

Soil depth	Management	pH	EC	Al-ox	Fe-ox
0–10 cm	Conventional	5.8 ± 0.1	44 ± 2.6	2.2 ± 0.1	5.4 ± 0.3
	Organic	6.1 ± 0.1	64 ± 5.0	2.1 ± 0.1	5.6 ± 0.2
	Meadow	5.7 ± 0.1	138 ± 4.3	3.2 ± 0.4	6.7 ± 0.4
10–20 cm	Conventional	6.0 ± 0.1	45 ± 2.7	2.2 ± 0.1	5.5 ± 0.3
	Organic	6.2 ± 0.1	55 ± 4.8	1.9 ± 0.1	5.7 ± 0.2
	Meadow	5.7 ± 0.1	58 ± 3.7	3.5 ± 0.3	7.7 ± 0.2
20–30 cm	Conventional	6.3 ± 0.1	42 ± 3.2	1.7 ± 0.1	3.6 ± 0.6
	Organic	6.4 ± 0.1	48 ± 7.3	1.8 ± 0.1	4.6 ± 0.5
	Meadow	5.8 ± 0.1	42 ± 5.9	2.9 ± 0.3	7.8 ± 0.0
30–40 cm	Conventional	6.8 ± 0.1	53 ± 0.6	1.7 ± 0.0	1.5 ± 0.2
	Organic	7.0 ± 0.1	37 ± 1.0	1.7 ± 0.0	1.7 ± 0.0
	Meadow	6.3 ± 0.2	40 ± 1.9	2.1 ± 0.2	6.3 ± 0.9
40–70 cm	Conventional	7.2 ± 0.1	49 ± 5.0	1.4 ± 0.0	1.4 ± 0.0
	Organic	7.4 ± 0.1	40 ± 2.5	1.4 ± 0.0	1.4 ± 0.0
	Meadow	6.9 ± 0.2	40 ± 2.0	1.5 ± 0.0	3.5 ± 1.0

The PVC tubes holding the intact soil columns were stored at −20 °C until summer (May–July) 2020. Tubes were defrosted to +4 °C and cut into 10 cm intervals while the soil remained in place inside the tube. After the cutting, the soil was pushed out from the 10 cm long tube sections. Part of the soil in each 10 cm soil section was air dried at +30 °C, and part stored at +4 °C.

Despite most of the one-meter long sampling cores penetrated the soil completely during soil sampling, they all contained <100 cm soil. Soil depths that the PVC tubes contained were; conventional: min. 62 cm, max. 76 cm, and average 69 (± SE 1.4) cm, organic: min. 64 cm, max 85 cm, and average 71 (± SE 2.0) cm, and unmanaged meadow: min. 62 cm, max. 73 cm, and average 68 (± SE 1.1) cm. There are several possible explanations for the cores not holding the full 100 cm of the soil. According to Persson and Bergström (1991), heavy clay soils that are near or in the water saturated state may stick to the edges of the tube and this may prevent the soil cutting motion of the edges and hence restrains the tube thoroughly penetrating the soil (Persson and Bergström, 1991). We contemplate the most probable reason for cores having <100 cm soil to be that lowest part of the soil columns from inside of the sampling tube have dropped back to the drilling hole when the tube was pulled out from the soil. Also, soil may be somewhat condensed during the sampling. However, judged by the soil bulk densities (Fig. A1) that are comparable with values reported for heavy clay soils from the area of the field experiment (e.g., Yli-Halla et al., 2009), we estimate this to be only a minor explaining factor.

For most of the laboratory analyses (except for soil textural analyses, see details below), soil layers down to 40 cm depth were kept separately in 10 cm layers, and soil layers below 40 cm (i.e., layers 40–50 cm, 50–60 cm, and 60–70 cm) were mixed to form one pooled sample. The decision to pool the layers below 40 cm was based on soil OC measurements performed for homogenized, air-dried subsamples of each 10 cm soil interval as in the soil depths 40–70 cm of all the studied profiles, the total soil OC concentrations were comparable (data not shown).

2.2. Soil properties and root biomass

Soil pH and electric conductivity (Table 2) were measured in 1:2.5 (w:v) soil-deionized water-solution. Soil was mixed into the water and incubated overnight at room temperature. The next morning, electric conductivity was measured from the unmixed sample, after which the sample was mixed and pH was measured immediately thereafter. Al- and Fe oxalates were extracted with acid ammonium oxalate extraction according to Niskanen (1989; 0.05 M oxalate, pH 3.3) using 5 g of air-dried soil. Al and Fe were measured with inductively coupled plasma mass spectrometry (ICP–OES Thermo Scientific iCAP 6300 MFC DUO).

Roots were washed from a subsample (~100 g of soil) that was stored at +4 °C prior to the washing, using tap water and a sieve with a mesh size of 125 μm. Before weighing, the roots were dried at +60 °C.

Soil texture (size classes: clay <2 μm; silt 2–20 μm; fine sand 20–200 μm; and coarse sand >200 μm) was analysed with the pipette method (Elonen, 1971). Soils were pre-treated with H_2O_2 for SOM removal, and then acidified with 2 M HCl and dispersed with 0.05 M $Na_4P_2O_7$. For texture analyses, air-dried soil was pooled together to create one sample per plot for each of the following soil depths: 0–20 cm, 20–40 cm and 40–70 cm (Table 3). The dominant clay mineral in the field is illite (X-Ray Diffractionation with Bruker D8 (Bruker Axs); minerals identified with Diffrac EVA 5.2 software. TOPAS 5.0 software for quantification WAXS measurements: 10–90°2θ; and SAXS measurements (for determining the d-values): 3–13°2θ).

2.3. SOM fractionation and metrics to estimate soil OC saturation

Samples were fractionated by size to MAOM (< 53 μm) and POM (> 53 μm) according to Cotrufo et al. (2019) with the exception that after testing the protocol, we decided to use field moist soil instead of air-dried soil to assist complete dispersion of the studied heavy clay soil (air-drying fortifies the existing aggregate structure and possibly creates new aggregates, e.g., Kaiser et al., 2015). In short, soil samples (around 5 g by dry weight) were sieved (mesh size 2 mm) and dispersed by shaking 18 h at 120 rpm (Ika LabortechnikKS 501 digital) with glass beads and 5 g l^{-1} sodium hexametaphosphate. After the dispersion, the suspension was rinsed on a sieve (mesh size 53 μm). The fraction that passed through the sieve was collected as MAOM, and the fraction that remained on top of the sieve was collected as POM. Fractions were dried to constant weight in a forced-air oven (60 °C). The level of soil dispersion was checked by using two internal reference soils (also field-moist; clay- and coarse textured soil) with each set of dispersed soils to confirm reproducible weights of the MAOM and POM. Samples were analysed for OC (MAOM-C and POM-C) by dry combustion (LecoCHN 628, St. Joseph, Michigan, USA). OC recovery was on average 97%, and ranged from 100 to 84%. All the analysed OC can be taken to represent OC due to the inherently low pH in Finnish soils as this prevents the formation of carbonate minerals (Nelson and Sommers, 1996).

DOM was extracted from air-dried soil (5 g) that was shaken in deionized water in 1:10 (w:v) ratio for 1 h at 180 rpm, and then left overnight at room temperature. Next morning, the sample was shaken for 15 min at 180 rpm and centrifuged for 10 min at 1069 *g* after which the solution was decanted and filtered (0.2 μm, Nucle-pore® polycarbonate, Whatman International Ltd) using a water suction. Dissolved carbon (DOM-C) was measured from the filtered solution with a Shimadzu TOC-V CPH/CPN analyser (Kyoto, Japan). When calculating the proportion of the total OC in each of the SOM fractions, the OC present in DOM-C was subtracted from MAOM-C as when performing the MAOM/POM fractionation procedure, we consider DOM-C to end up in the MAOM fraction (i.e., to pass through the 53 μm sieve).

Table 3
Soil texture, average across the field (n = 3).

Soil depth	Management	Coarse sand	Fine sand	Silt	Clay
		> 200 μm	200–20 μm	2–20 μm	< 2 μm
		g kg^{-1}			
	Conventional	100	200	170	530
0–20 cm	Organic	110	200	160	530
	Meadow	24	170	126	680
	Conventional	40	190	140	640
20–40 cm	Organic	40	180	160	620
	Meadow	15	160	115	710
	Conventional	0	167	173	660
40–70 cm	Organic	0	186	154	660
	Meadow	0	180	140	680

Soil texture was used to estimate the MAOM-C accrual capacity for each soil. We calculated the capacity of fine-sized particles (clay+silt, < 20 μm) to stabilise MAOM-C using the Hassink (1997) Equation: MAOM-C (g kg^{-1}) at OC saturation = 0.370 × (clay+silt%) + 4.09. We also used the theory by Dexter et al. (2008) by which the soil OC saturation state can be estimated with clay to OC ratio. A ratio below 10 indicates that mineral surfaces are saturated with OC, and a ratio above 10 suggests OC saturation deficit. These accrual capacity estimations were compared with measured MAOM-C to assess the potential for further MAOM-C accrual for the cultivated soils.

Laboratory analyses were performed for each soil depth layer (i.e., 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm, and 40–70 cm) from each of the sampling tubes (leading to $n = 9$ per depth layer and soil management). For the data analyses, the results of the laboratory analyses were averaged plotwise (leading to $n = 3$). For variables of total C, the mass and OC content of SOM fractions, and Al and Fe oxides within a depth per plot, the coefficient of variation (CV) was calculated from three plot replicates. Where within a plot variation exceeded 20%, samples were re-analysed to ascertain the high level of variation.

2.4. Data analyses

All statistical analyses were performed with R (R Core Team, 2022, version 4.1.3). Analyses were performed between conventional and organic cropping systems as the unmanaged meadow was not a part of the randomized block design and therefore not included in the statistical analyses. Since some of the data was not normally distributed and had unequal variances, we used the nonparametric Kruskal-Wallis test to determine possible differences in the forms of carbon (MAOM-C, POM-C and DOM-C), Clay to OC ratio, and C to N ratios of the bulk soil, MAOM and POM. We regarded *p*-values of 0.05 or less as statistically significant.

For comparing soil carbon stocks, we used the Fixed depth (FD) intervals and Equal soil mass (ESM) approach (e.g., Wendt and Hauser, 2013; Von Haden et al., 2020), and Kruskal-Wallis test for determining statistical differences in the OC stocks between the cropping systems. In the fixed depth approach, soil carbon stocks were calculated as follows: OC stock (t OC ha^{-1}) = OC concentration (g OC kg^{-1} soil) × soil bulk density (kg m^{-3}) × depth of a soil layer (cm) /1000. We estimated soil OC stocks also with the ESM method as FD may be prone to errors caused by compaction during the sampling and the following segmenting the soil into FD layers (e.g., Wendt and Hauser, 2013, Von Haden et al., 2020). The ESM method may also more accurately reflect the true state of the soil OC stocks when comparing differing managements as it disregards possible differences in the soil density that are derived from soil management and/or SOM content. ESM OC stock calculations were performed with the Excel spreadsheet from Wendt and Hauser (2013). For the Fixed depth OC stock calculations, we scaled all the sampling tubes to 70 cm soil depth (actual sampling depths were 62–85 cm, see Section 2.1). For the ESM OC stock calculations, we estimated the OC stocks to the soil mass of 7500 t ha^{-1} (this soil mass is reached in the soil depth of 57.0 (±0.8) - 62.3 (0.8) cm; Table A2) as all of the sampling tubes (with one exception) contained this soil mass when the area of the sampling tube was scaled to a hectare. One sampling tube from the unmanaged meadow contained 7390 t ha^{-1} of soil and was extrapolated to represent the soil mass of 7500 t ha^{-1}. As we wanted to avoid further extrapolations, we decided to assess the soil OC stocks to the soil mass of 7500 t ha^{-1} throughout the field.

As ESM and FD methods gave resembling results, and the soil bulk densities did not imply differing soil compaction in any of the soil depth layers between the management systems when sampling (Fig. A1), further detailed analyses (MAOM/POM/DOM fractionation, Al and Fe oxide extraction, root biomass analyses) were performed for the fixed depth soil layers (FD). Similarities of the soil bulk densities gave additional support for the reliability of the comparisons of the OC stocks and other studied parameters of the soil layers with both approaches, FD and ESM.

We applied Spearman rank correlation analyses to estimate the association between soil properties (clay content, and Al and Fe oxide contents) and total OC, MAOM-C, and POM-C. Soil profiles of conventional and organic cropping systems, and the adjacent unmanaged meadow were analysed in three depth segments: 0–20 cm, 20–30 cm and 30–70 cm. Analyses were performed within a depth segment for soil samples with all the managements combined. We selected these specific layers as we observed the highest variation in most of the studied variables in the soil layer of 20–30 cm, which we believe to expresses that ploughing affects to some extent also the soil below 20 cm in the cropped systems, causing heterogeneity in this layer. The plough layer of 0–20 cm was assumed to be relatively homogenous due to the regular mixing effect from the ploughing, and the depth 30–70 cm was also assumed relatively homogenous as it is not disturbed by the tillage operations. All the plots were created using R packages ‘ggplot2’, ‘ggpubr’ and ‘ggbreak’ (Wickham et al., 2016; Kassambara, 2020; Xu et al., 2021).

3. Results

3.1. Soil carbon stock in the unmanaged meadow in relation to the cultivated soil

Total soil OC stock down to 70 cm depth in the unmanaged meadow was 169 t ha^{-1} (± SE 6.94) which was 1.5-fold compared to the conventional (112 t ha^{-1} ± SE 3.32), and 1.3-fold compared to the organic (129 t ha^{-1} ± SE 3.88) cropping system. The OC stocks of the unmanaged meadow were higher in all the individual (FD) soil layers (Fig. 1A) than in the cropping systems. In all the soil management types, most of the OC, around 85%, was in the top 30 cm of the soil, where also most of the plant root biomass was located (Fig. 1B). The unmanaged meadow had distinctly larger root biomass in the uppermost soil layers when compared to the cropping systems; in the soil depth of 0–10 cm, root biomass in the meadow was around 5-fold, in the layer 10–20 cm around 3-fold, and in the 20–30 cm soil depth more than double compared to the cropping systems. Within the cropping systems, root biomass tended to be larger in the organic than in the conventional system.

3.2. Soil carbon stocks in organically and conventionally managed cropping systems

We determined the total soil carbon stocks of the cropping systems to the equivalent soil mass of 7500 t ha^{-1}. In the whole of this soil mass, the OC stock was significantly higher in the organic (125 t ha^{-1} ± SE 1.3) than in the conventional cropping system (107 t ha^{-1} ± SE 1.3, *p*-value 0.04953). Further, we divided the soil mass into three layers: 0–1500 t ha^{-1}, 1500–3000 ha^{-1} and 3000–7500 t ha^{-1} (see Table A2 for the soil depths (cm) in which the Equal soil masses were reached). When comparing these individual layers, the 1500–3000 t ha^{-1} layer had significantly larger OC stocks in the organic (48 t ha^{-1} ± SE 2.8) than in the conventional (35 t ha^{-1} ± SE 2.8) cropping system (p-value 0.04953). The upper (0–1500 t ha^{-1}) and lower (3000–7500 t ha^{-1}) layers had resembling OC stocks in both of the cropping systems; OC stocks were in the upper layer 53 t ha^{-1} (± SE 1.0) in the conventional, and 57 t ha^{-1} (± SE 1.3) in the organic; and in the lower layer 19 t ha^{-1} (± SE 1.3) in the conventional, and 20 t ha^{-1} (± SE 0.8) in the organic system.

When considering the total OC stocks by depth (to 70 cm; Fig. 1), rather than mass, we observed a significantly larger stock in the organic than in the conventional cropping system (*p*-value 0.04953). The total OC stocks were on average 17 t ha^{-1} larger in organic than in the conventional cropping system, corresponding to a yearly difference of 0.7 t ha^{-1} in OC stock. In the topmost soil layer of 0–10 cm, OC stocks were comparable (34 t ha^{-1} conventional, and 35 t ha^{-1} organic) but in the soil depths from 10 to 30 cm, the organic cropping system had larger OC stocks than the conventional system (layer 10–20 cm: organic 44 t ha^{-1}, conventional 41 t ha^{-1}; layer 20–30 cm: organic 31 t ha^{-1}, conventional 19 t ha^{-1}, *p*-value 0.04953). Below 30 cm, OC stocks were similar: in the layer 30–40 cm, the conventional system had 6 t OC ha^{-1}, and the organic system 7 t ha^{-1}. In the deepest studied soil layer of 40–70 cm, both of the cropping systems had a OC stock of 12 t OC ha^{-1}.

3.3. Distribution of soil OC to MAOM and POM fractions

In all the studied FD soil depths, the majority of soil C, 83–97%, was in the MAOM fraction (Table A1). The proportion of soil OC in the POM fraction was at its highest close to the soil surface (0–30 cm) and decreased with soil depth. The distribution of soil OC between SOM fractions did not differ statistically between organic and conventional cropping systems but there was a tendency of higher MAOM-C, POM-C, and DOM-C in the organically managed system (Table 4).

In general, there was a strong positive relationship between total soil OC content and the amount of OC in all the studied SOM fractions in the

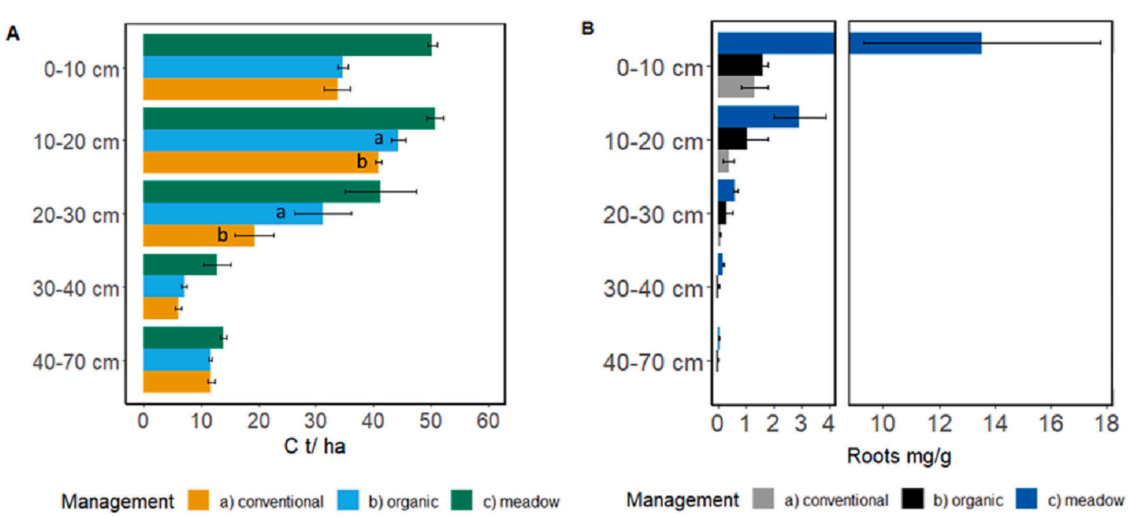

Fig. 1. A) Distribution of soil organic carbon stocks (t ha^{-1}) in the cropping systems (conventional and organic) and unmanaged meadow (±SE, $n = 3$) in Fixed depth soil layers to 70 cm soil depth. Statistical analyses were performed only between the conventional and organic cropping systems, and letters a and b denote statistical differences within a soil layer (Kruskal-Wallis test, p- value 0.04953). B) Root mass (mg in g^{-1} of soil) in the soil depth layers (±SE, n = 3). Roots were observed in all the soil depths of unmanaged meadow and organic cropping system, but in the conventional system, there were no measurable amounts of roots below the soil depth of 30 cm (neither from the root washing procedure nor in visual inspection). Note the break in the x-axis.

Table 4
Average (±SE, n = 3) organic carbon concentrations of total soil, MAOM, POM and DOM, clay to OC-ratio, estimated MAOM-C accrual potential (g kg^{-1}) and the realized MAOM-C accrual (i.e., the measured OC content (%) from the estimated accrual potential) according to Hassink's Equation, and C to N ratios of the bulk soil, MAOM and POM per soil depth and cropping system. The total soil C to N ratio was calculated from the MAOM and POM C and N content. Statistical analyses were performed only between the conventional and organic cropping systems (except for Hassink's Equation), and letters a and b denote statistical differences within a soil layer (Kruskal-Wallis test; all statistically significant tests had a *p*-value 0.04953).

Soil depth	Management	Total soil OC g kg^{-1}	MAOM-C g kg^{-1}	POM-C g kg^{-1}	DOM-C mg g^{-1}	Clay to OC ratio	Hassink's Equation		C to N ratio		
							MAOM-C accrual potential (g kg^{-1})	Realized MAOM-C accrual (%)	Bulk soil	MAOM	POM
0–10 cm	Conventional	32.8 ± 1.2	28.6 ± 0.6	4.2 ± 0.8	0.33 ± 0.01	16 ± 1.1	29.6	97 ± 2.9	13 ± 0.7	12 ± 0.6	23 ± 5.8
	Organic	35.5 ± 0.8	29.6 ± 1.2	5.9 ± 0.5	0.36 ± 0.07	15 ± 0.7	29.8	99 ± 5.7	12 ± 0.3	11 ± 0.4	19 ± 0.4
	Meadow	70.0 ± 2.5	59.5 ± 1.7	10.5 ± 0.8	0.86 ± 0.03	10 ± 0.6	33.9	176 ± 7.7	14 ± 1.1	14 ± 1.3	18 ± 0.9
10–20 cm	Conventional	32.0 ± 1.4	27.2 ± 1.1	4.8 ± 0.9	0.28 ± 0.01	17 ± 1.3	29.6	92 ± 3.8	13 ± 0.6	12 ± 0.6	21 ± 1.5
	Organic	35.1 ± 0.9	29.5 ± 0.9	5.6 ± 0.5	0.31 ± 0.05	15 ± 0.7	29.8	99 ± 4.8	12 ± 0.3	11 ± 0.4	19 ± 0.4
	Meadow	46.9 ± 1.8	42.3 ± 1.6	4.6 ± 0.2	0.51 ± 0.06	15 ± 1.0	33.9	125 ± 6.3	14 ± 0.2	14 ± 0.1	23 ± 3.9
20–30 cm	Conventional	**13.5 ± 2.3[a]**	**11.7 ± 1.8[a]**	1.8 ± 0.7	**0.12 ± 0.00[a]**	57 ± 13.6	32.9	36 ± 6.7	11 ± 1.1	11 ± 0.8	16 ± 3.1
	Organic	**22.4 ± 3.9[b]**	**19.0 ± 3.5[b]**	3.4 ± 0.5	**0.22 ± 0.03[b]**	40 ± 10.8	32.8	58 ± 12.1	12 ± 0.7	11 ± 0.7	19 ± 1.1
	Meadow	32.9 ± 5.2	30.4 ± 4.6	2.4 ± 0.7	0.33 ± 0.07	26 ± 6.5	34.4	89 ± 15.4	15 ± 0.4	15 ± 0.3	27 ± 6.5
30–40 cm	Conventional	4.1 ± 0.3	3.9 ± 0.3	0.2 ± 0.0	**0.06 ± 0.00[a]**	158 ± 17.0	32.9	12 ± 0.7	7 ± 1.6	7 ± 1.6	8 ± 1.9
	Organic	4.9 ± 0.3	4.5 ± 0.2	0.3 ± 0.1	**0.09 ± 0.01[b]**	131 ± 8.0	32.8	14 ± 1.0	6 ± 0.4	6 ± 0.4	11 ± 0.8
	Meadow	9.0 ± 1.6	8.5 ± 1.4	0.5 ± 0.1	0.11 ± 0.01	98 ± 15.7	34.4	25 ± 4.9	14 ± 2.8	14 ± 2.8	10 ± 3.0
40–70 cm	Conventional	2.6 ± 0.1	2.5 ± 0.1	0.1 ± 0.0	0.04 ± 0.00	**254 ± 4.6[a]**	34.9	7 ± 0.1	8 ± 3.3	5 ± 0.4	7 ± 1.2
	Organic	2.7 ± 0.1	2.6 ± 0.1	0.1 ± 0.0	0.05 ± 0.00	**246 ± 1.8[b]**	33.3	8 ± 0.1	5 ± 0.2	5 ± 0.2	7 ± 0.5
	Meadow	3.3 ± 0.2	3.0 ± 0.2	0.2 ± 0.0	0.06 ± 0.00	215 ± 6.0	34.4	9 ± 0.6	8 ± 0.4	7 ± 0.5	9 ± 3.2

cropping systems (i.e., OC was comparably shared into MAOM-C, POM-C, and DOM-C with different OC levels; Table 4, Fig. 2A and B, Table A1). Total OC content of the soil samples varied between 2.6 and 70 g kg^{-1} (Table 4), and the MAOM-C was linearly related to the total OC content (Fig. 2A). Similarly, the highest POM contents were measured in soils with the highest OC contents (Fig. 2B), but the variation in the OC content of POM was larger than in MAOM. In the soil depth of 20–30 cm, total OC and MAOM-C were larger in the organic than conventional cropping system (Table 4, p-value 0.04953). The amount of DOM-C was significantly correlated to total C, and larger in the organic than in the conventional cropping system in the soil depths of 20–30 cm and 30–40 cm (p-value 0.04953). Bulk soil C to N ratios were higher in the topsoil (0–30 cm) than deeper in the soil. C to N ratios tended to be lower in the MAOM than in the POM down to 30 cm depth but below that this difference narrowed down, and the values were closer to each other (Table 4).

3.4. Soil OC saturation state, and MAOM-C and POM-C along the soil profile in relation to soil properties

When the capacity of soil to accrue OC was estimated based on the clay to OC ratio (Table 4), the surface soil (0–10 cm) of the unmanaged meadow had on average a clay to OC ratio of 10, indicating that the mineral surfaces were close to or at the OC saturated state. However, already in the soil layer of 10–20 cm, the ratio was 15, implying an OC saturation deficit. In the cropping systems, the clay to OC ratios in the plough layer (0–20 cm) varied between 15 and 17, also indicating an OC saturation deficit. Below the soil depth of 20 cm, all the soils had a saturation deficiency as judged by clay to OC ratios; they were larger than 10 (26–254) for all the studied soils.

When estimating the saturation point of MAOM-C with the Hassink's Equation (Hassink, 1997), the topsoil layers of the unmanaged meadow were above maximum saturation; soil layer 0–10 cm had reached 176%, and the layer 10–20 cm 125% of the estimated saturation OC level. Also topsoil layers of the cropping systems were very close to or at the MAOM-C saturated state when estimated with the Hassink's Equation. In the ploughed layer, MAOM-C saturation was 97% and 99% in the conventionally managed fields and 92% and 99% in the organically managed fields in the 0–10 and 10–20 cm soil layer, respectively. However, in soil layers below 30 cm, all the soil management types had low MAOM-C and were estimated to have potential to accrue MAOM-C. It is noteworthy that despite both clay to OC ratio and Hassink's Equation showed that all topsoils were close or even above OC saturation, the OC to MAOM-C ratio (Fig. 2A) did not show any indications of MAOM-C saturation, not even at the levels higher than 60 g kg $^{-1}$ of total soil carbon.

In the topsoil (0–20 cm), Al-ox and clay, and Al-ox and Fe-ox were strongly correlated, whereas deeper in the soil (30–70 cm) the individual oxides were not correlated with each other but correlated with clay in different soil depths; Al-ox in 0–30 cm, and Fe-ox in 30–70 cm (Table 5). Spearman rank correlation analyses showed clear positive relationship between clay content and total OC and MAOM-C in the topsoil (0–20 cm, Fig. 3). However, below 20 cm soil depth, clay content could not be connected to the total OC nor the MAOM-C or POM-C. Al-ox and Fe-ox were significantly associated with both total OC and MAOM-C in the most of studied soil layers (0–70 cm), but in the soil depth of 20–30 cm only Fe-ox correlated with total OC and MAOM-C whereas Al-ox was more strongly correlated with these below 30 cm depth. In the soil depths from 0 to 30 cm, Spearman correlation analyses did not link any of the soil properties to POM-C, but in the 30–70 cm, correlation between Al and Fe oxides and POM-C was found.

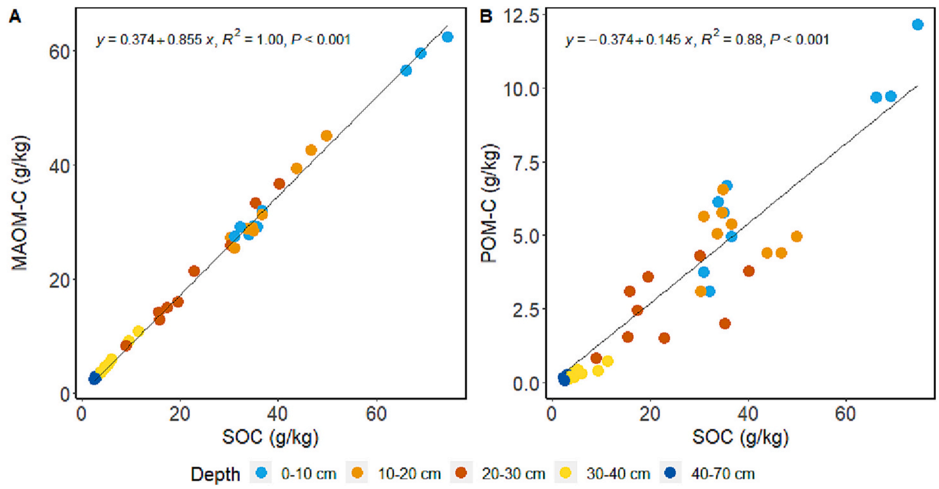

Fig. 2. The soil organic OC content versus MAOM-C (A), POM-C (B; $n = 9$ per soil depth layer). Graphs are based on the data from all soil depths in both cropping systems and the unmanaged meadow. Note differing y-axis scales.

4. Discussion

4.1. OC stocks and plant roots across soil depths

The largest soil OC stock and plant root biomass were observed from the unmanaged meadow when compared to the conventional and organic cropping systems (Fig. 1). The unmanaged meadow having the highest OC stocks despite not receiving additional nutrient- or OC inputs in the past 24 years illustrates the high potential of undisturbed ecosystems with perennial plants to either accumulate new OC to the soil or both, accumulate new OC and maintain high OC stocks from the previous land use. The unmanaged meadow and the cropping systems had the same land use history as an extensively managed grassland before the start of the experiment (prior to 1995), dating back at least to the beginning of the 20th century (excluding some exceptions during 1989–1995; see Section 2.1). Prior to land clearing, the site of the field experiment was a forest (Gylden, 1850). In general, the long-term effects of forest clearance depend on the subsequent land use: in northern latitudes, soil OC stocks tend to drop after conversion to an arable field (Guo and Gifford, 2002; Heikkinen et al., 2013), but increase if the change is from forest to pasture (Guo and Gifford, 2002; the unmanaged meadow studied in here may be accounted to resemble a pasture). Consistent with this, the OC stocks of the unmanaged meadow in our study were four times greater compared to the reported OC stocks of boreal forest soils around the same latitude in Scandinavia (including Finland; average of 41 t ha^{-1} OC to one meter depth, Callesen et al. (2003)). However, as the remaining forests in Scandinavia are mainly growing on coarser soils with limited OC binding capacity whereas inherently more fertile, fine-textured soils have been cleared for agricultural production (Heikkinen et al., 2013), OC stock comparisons should be done with great caution and preferably taking soil texture into consideration. As the baseline OC stocks at the start of the field experiment were not measured, it is not possible to ascertain the origin of the high OC stocks of the unmanaged meadow. Nevertheless, there are indications of increase in the OC stocks as they were 15–53% larger in all the observed soil layers of the meadow than in the cultivated systems. We also found the unmanaged meadow to be closer to the OC saturation (see Section 4.5). Therefore, there are implications that perennial plants, with high OC input from plant litter and root exudates (e.g., Jackson et al., 2017; Bai and Cotrufo, 2022) combined with a lack of disturbances are a potentially effective means of sequestering new OC to the soil.

Focusing on the cropping systems, organically managed soil had higher OC stocks in the studied profile (0–70 cm; Fig. 1A) than the conventional cropping system after 24 years of unchanged management. Before the start of the field experiment (in 1990), OC concentrations of the topsoil (c. 0–25 cm, see Section 2.1) in the experimental field and in the adjacent, unmanaged meadow were uniform, and higher than the OC concentrations we measured from the cropping systems in 2019 (Table 4). This indicates that the change from extensively managed grassland to the crop rotations (in 1995) may have decreased soil OC in the cultivated soils whereas in the unmanaged meadow, lack of disturbance and abundant plant root biomass have enabled maintaining higher level of the soil OC stocks. Between the cultivated systems, OC levels have decreased more in the conventional than in the organic cropping system. Higher measured OC levels of the organic systems are in line with several other studies reporting that organic management practices can increase the size of the soil OC stocks (e.g., Leifeld and Fuhrer, 2010; Kätterer et al., 2014; Tiefenbacher et al., 2021), although the amount of applied fertilizer-OC is an important determinant for the size of the OC stocks (Maillard and Angers, 2014; Bolinder et al., 2020). As part of the manure can be decomposed relatively fast after its application to the soil (Maillard and Angers, 2014), the larger OC stocks in the organically fertilized soils are likely to derive from both the continuous OC additions from the applied manure and from the root inputs.

Table 5
Spearman rank correlation coefficients (ρ) for the soil clay content (%), aluminum (Al-ox, g kg^{-1}) and iron (Fe-ox, g kg^{-1}) oxides in different soil depths. Significant correlations bolded ($p < 0.05$).

Soil depth											
	0–20 cm				20–30 cm				30–70 cm		
	Clay	Al-ox	Fe-ox		Clay	Al-ox	Fe-ox		Clay	Al-ox	Fe-ox
Clay	1			Clay	1			Clay	1		
Al-ox	**0.56**	1		Al-ox	**0.87**	1		Al-ox	−0.08	1	
Fe-ox	0.44	**0.71**	1	Fe-ox	0.42	0.57	1	Fe-ox	0.27	**0.68**	1

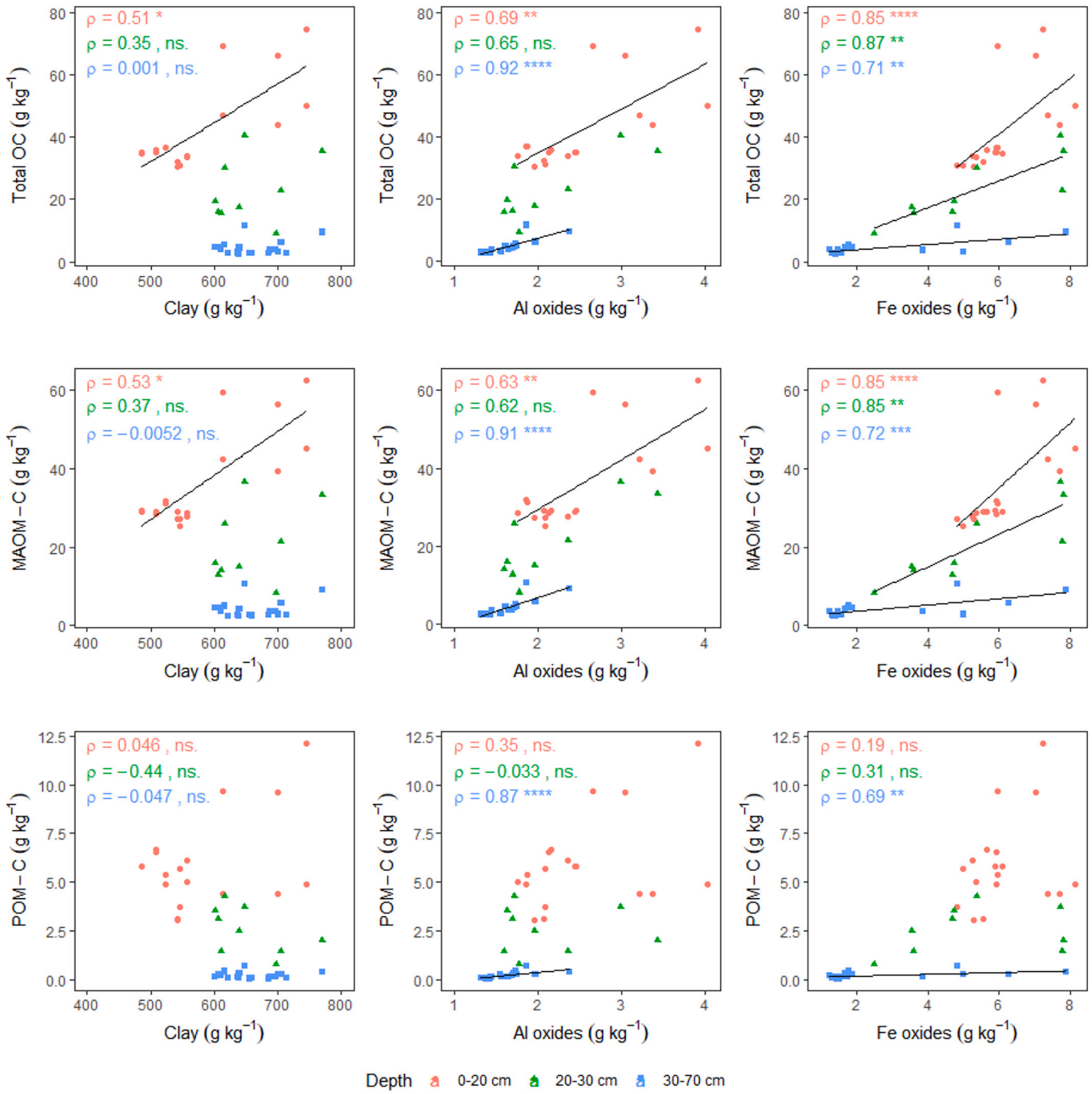

Fig. 3. Spearman rank correlations between total soil OC, MAOM- C and POM-C, and the soil properties clay, Al- and Fe oxides (g kg^{-1}). Analysis was performed for all the soil samples from all the management systems (conventional and organic cropping systems and unmanaged meadow) in three depth intervals: 0–20 (contains depths 0–10 cm and 10–20 cm ($n = 18$), 20–30 cm ($n = 9$), and 30–70 cm (contains soil depths 30–40 cm and 40–70 cm, n = 18). Significant p-values are marked as follows: < 0.05 = *, < 0.01 = **, <0.001 = ***, and 0.0001 = ****. In case of a significant correlation, regression line added to illustrate the relation between soil properties and OC fraction.

Although both studied cropping systems had similar crop rotation and soil management (see Section 2.1), roots were found growing deeper in the organic system (Fig. 1B). The deeper rooting depth and larger root biomass in the organic system was not a consequence of any apparent physical limitations (such as a plough pan or higher bulk density) keeping the roots in the conventional system from growing deeper (Fig. A1). The differing root growth patterns in the two cropping systems may relate to a nutrient acquisition strategy of plants as the organic system received less phosphorus and nitrogen (both in total and in a soluble form) than the conventional system (see Section 2.1). However, it is noteworthy that organic cropping systems typically have a larger density of weeds than conventional systems (Bàrberi, 2002). In this work, we did not have a possibility to distinguish which portion of the root biomass originated from the cropped plants and which from the weeds, but it is probable that the density of the weed roots was higher in the organic system. Nevertheless, roots are shown to be efficient in increasing soil OC levels in Nordic conditions as they have been shown to contribute to the OC accumulation as much as organic amendments in an organic system in Sweden (Menichetti et al., 2015). In addition to plant-root derived OC additions, ploughing (to 20 cm depth in both cropping systems) and leaching may contribute to the translocation of part of the organic fertilizer from the topsoil to deeper soil layers (Button et al., 2022), due to which roots may grow deeper to reach the nutrients mineralised from the organic fertilizer (Chapman et al., 2012).

While topsoil (0–15 cm) OC stocks in the cropping systems (54 t ha^{-1} in the conventional, and 56 t ha^{-1} organic management) were comparable to each other and to the national average for the Finnish mineral arable soil (54 t OC ha^{-1}, Heikkinen et al. (2013)), differences in total OC stocks between the cropping systems derived primarily from the organic system having a higher OC stocks in the soil depth of 10–30 cm (Fig. 1A). In both the organic and conventional management systems, the soil is ploughed to a depth of 20 cm within 12–14 months from fertilizer application, resulting in inversion tillage being applied >10 times over a 24-year period from the start of the field experiment to our sampling. This may be an important reason for the significant difference in OC stock between the organic and conventional management systems at 20–30 cm soil depth. Boreal climatic conditions hinder the mineralization of organic fertilizer, and this is particularly evident in the subsoil where lower oxygen levels and colder temperatures result in the longer-term preservation of OC (Ogle et al., 2019).

In the 30–40 cm soil depth, we observed probable effects of organic fertilising and/or root inputs as the OC stocks in this soil layer were 16% larger compared to the conventionally managed fields. However, we cannot quantify which part of soil OC originated from the organic fertilization, and which part was of plant origin. In the subsoil (40–70 cm), the differing fertilization management had no effect on the OC stocks, suggesting that the rate of OC accumulation in the subsoil was indeed slow (Button et al., 2022). The rooting patterns of the arable crops may restrict subsoil OC accrual as the belowground OC allocation can be <10% of the photosynthesized OC in the croplands (Jackson et al., 2017). The slow increase in subsoil carbon compared to the higher soil depths (0–40 cm) is supported by Kätterer et al. (2014) who reported that during 13 years of field treatments in Sweden, organic amendments were responsible for as much as 27% of OC stock increase in the upper subsoil (25–40 cm), but with no observable effects on soil OC stocks below the 40 cm.

4.2. Distribution of soil OC to MAOM and POM fractions

The majority of soil OC was in the MAOM fraction (Table A1). Throughout the soil profile, we found that only 3–17% of the OC was associated with the POM-fraction. As expected, the share of OC in the POM tended to be higher in the topsoil (10–17% of soil OC in POM in 0–20 cm) where the plant litter production and root exudation are more abundant than in deeper soil depths (3–15% of soil OC in POM in 30–70 cm). However, the proportion of soil OC in the POM fraction was lower than expected when compared to the findings of Sokol et al. (2022), who reported a global average of 35% of the total OC found in the POM fraction in mineral soils, and Guillaume et al. (2022) who reported 20% for temperate climate conditions despite the land use. This can in part be explained by methodological observations. We utilized the fractionation method of Cotrufo et al. (2019) with the application of glass beads to assist dispersion due to the high clay content of the soils. The glass bead approach likely results in some crumbling of the larger POM fragments into finer pieces (< 53 μm). This fine-sized POM passes through the sieve to the MAOM-fraction leading to a somewhat overestimating the MAOM-C pool. On the other hand, despite the dispersion with glass beads, we observed some very stable aggregates (> 53 μm) in the POM fraction. While occluded POM inside these dispersion-resistant aggregates (often aggregates build surrounding POM; Besnard et al., 1996, Totsche et al., 2018) belongs in the POM-C pool, their mineral matrix contains some MAOM-C, falsely determined as POM-C. Despite it being likely that some portion of OC from both SOM fractions was determined in the incorrect OC pool, we assume that this represents a relatively minor source of error as these errors would at least partly cancel each other out.

4.3. C to N ratios of the bulk soil and MAOM and POM fractions

C to N ratios of the total soil and MAOM were closely corresponding (Table 4; C in the C to N ratio can be accounted as OC). The C to N ratios of the topsoil were comparable to what were found in cereal cropping systems on a clay soil in Finland (Soinne et al., 2021), but slightly higher than reported from Sweden (Börjesson et al., 2018). The C to N ratio for total soil and MAOM ($C/N = 5$ –15 for both) was lower than for POM (C/N = 7–27) throughout the soil profile (0–70 cm). Our findings are comparable with the literature (Lavallee et al., 2020) as C to N ratios tended to be lower in MAOM ($C/N = 8$–13) than in POM ($C/N = 10$–40). In the subsoil (40–70 cm), the C to N ratio of POM (C/N = 7–11) was reduced and resembled that of the MAOM (C/N = 5–14) which is in line with Rumpel and Kögel-Knabner (2011) who also found C to N ratios to be higher in the topsoil than deeper in the soil. The lower C to N ratio of the POM fraction in the subsoil (below 30 cm) and its significant correlation with the Al and Fe oxides (Fig. 3) may signal resembling quality of the operational SOM fractions MAOM and POM (Yu et al., 2022) deeper in the soil. The shift of POM C to N ratio with depth from a ratio similar to plant material in the topsoil to a ratio comparable to the microbial biomass (Miltner et al., 2012) in the subsoil implies that a larger relative share of the OC is microbially processed in the subsoil than in the topsoil (Button et al., 2022).

4.4. Assessing soil OC saturation state

We estimated the soil MAOM-C saturation state from the relationship between total soil OC and MAOM-C. A total OC content of 50 g kg^{-1} is suggested to be a flex point soil OC concentration where new soil OC begins mainly to accrue to the POM-C fraction (Stewart et al., 2007; Cotrufo et al., 2019). In our data, the relationship between total soil OC and MAOM-C remained linear also above the suggested flex point concentration (Fig. 2A), indicating that in soils with high clay content, the MAOM-C accrual capacity may exceed the proposed maximum of 50 g kg^{-1}. Similarly, the MAOM-C content at the surface soil of the unmanaged meadow surpassed the estimate of its accrual capacity calculated according to Hassink's Equation (Hassink, 1997; Table 4) as it was 125–176% in 0–20 cm, and the plough layers (0–20 cm) of the cropping systems were found to be near or at saturation (92–99% of the estimated accrual capacity with the Hassink's Equation). These findings indicate that assessing the MAOM-C accrual capacity based solely on the soil OC content (Cotrufo et al., 2019) or with approaches that only include the share of clay and silt fraction (e.g., Hassink, 1997) will lead to an underestimation of the MAOM-C accrual capacity in heavy clay soils.

In addition to the larger specific surface area of clay-sized particles and therefore the larger mass-based sorption capacity compared to silt-sized particles, the capacity of clay soils to accrue MAOM may be enhanced due to the formation of small microaggregates (< 20 μm) in which the clay-sized particles and microbially derived organic materials act as building units (Totsche et al., 2018). Encrustation of clay-sized particles around an organic molecule can lead to the formation of very stable aggregates (Zimmermann and Horn, 2020) that are able to increase the OC protection capacity even after the full MAOM-C surface sorption potential is reached. We found very stable aggregates (or precipitates) after the MAOM-POM fractionation procedure (See Section 4.2), especially in the soils from the conventional and organic crop rotation systems. A reason for aggregates being more prevalent in the cropping systems may be the lower SOM content compared to the unmanaged meadow. In the meadow systems, high OC levels may lead to complexation of Al and Fe with SOM, which may disturb the further precipitation of these metals towards more crystalline forms and therefore reduce their aggregate-stabilizing effect in the unmanaged meadow (Hall and Thompson, 2022). However, as the interactions with SOM and metals in oxide precipitation-dissolution processes and aggregate formation are very complex, more research is needed to verify the origin of these very stable aggregates.

We also used the clay to OC ratio for assessing the C- saturation state of the soil. Dexter et al. (2008) suggested that the maximum capacity of mineral soils to bind OC would be reached at a clay to OC ratio of 10 as 1 g of OC can be at maximum complexed by 10 g of clay. We found that the clay to OC ratio in the uppermost surface soil (0–10 cm) of the unmanaged meadow was 10 (Table 4), suggesting that based on this measure, the topsoil of the meadow has reached C saturation. The clay to OC ratios also suggested that at most soil depths the cropping systems were more carbon deficient than in the unmanaged meadow, except for the soil layer of 10–20 cm where comparable clay to OC ratios were found (ratios between 15 and 17). The similarity of ratios in this soil layer is probably caused by the ploughing of the cropping systems as this introduces organic matter below the topmost surface soil layer (here, below 10 cm), leading to a relatively homogenous OC content throughout the plough layer (in studied experimental field, 0–20 cm). At the same time, soil OC content in the unploughed meadow was found to be highest between 0 and 10 cm and decline in the 10–20 cm layer, leading to an abrupt increase in clay to OC ratio (i.e., the soil was further away from OC saturation) below the top 10 cm layer of the soil.

Below the depth of 30 cm, we found high (from 26 to 254) clay to OC ratios in all the studied management systems, implying potential for further MAOM-C accrual. Also, this demonstrates that reaching the OC saturation below the top soil likely requires active incorporation of external OC inputs (for example by ploughing). In the deepest studied soil depth (40–70 cm), the clay to OC ratio of the organically managed system was significantly lower than in the conventional system. At such deep soil depths all systems remained well away from the OC saturation as their clay to OC ratios were higher than 200. However, it may not be meaningful to estimate the MAOM-C accrual capacity of the deeper soil layers (below 40 cm) based on the same metrics as in the surface soil layers, since physical, biological and often also chemical properties differ from the surface soil (Salome et al., 2010; Liebmann et al., 2020) which may hamper the OC accrual in the deep soil.

4.5. Role of clay, and Al and Fe oxides in transporting and storing OC

In addition to management induced translocations, OC moves down in the profile via leaching as DOM-C (Kaiser and Kalbitz, 2012; Button et al., 2022) and attached to mineral surfaces as MAOM-C with clay illuviation (Yli-Halla et al., 2009; Torres-Sallan et al., 2017). The larger DOM-C concentrations in the soil layers of 20–30 and 30–40 cm in the organic cropping system may indicate dynamic cycling of OC originating from the organic amendments and rhizodeposition. Downward movement of OC can be facilitated by large biopores and other cracks, such as old root channels and earthworm burrows, that form preferential flow paths in heavy clay soils such as the one studied here (Shipitalo et al., 2004). Deeper in the soil, DOC may be stabilised again by interactions with Fe and Al oxides (Rumpel and Kögel-Knabner, 2011). In addition, downward movement of OC can be initiated when organic acids (for example root exudates) enhance the dissolution of minerals and therefore increase the solubility of aluminum and iron (Bais et al., 2006). Soluble complexes of Al and Fe with organic ligands can leach through the soil profile during which the physicochemical properties of the surrounding soil support their alternating precipitation and remobilisation cycles (i.e. podzolisation; Lundström et al., 2000). Therefore, the tight relationship between Al and Fe oxides, OC and MAOM-C along the soil profile may also indicate DOC-driven relocation of dissolved metals in which case the oxalate extractable Al and Fe would be responding to instead of driving the OC content as was suggested by Hall and Thompson (2022). Whichever the mechanism that translocates OC in the soil profile, the observed positive relationship between OC and DOC encourages the strive for reaching high OC content in the surface soil. The infiltration and percolation of water into the soil profile can support a continuous yet slow seeping of OC down into the soil profile, where it could potentially be stored for a long time.

5. Conclusions

After 24 years from the start of the field experiment, the organically managed system had larger OC stocks (17 t ha^{-1} in the 0–70 cm) compared to the conventionally managed cropping system (OC stocks 129 and 112 t ha^{-1} in the organic and conventional system, respectively). Specifically, the organically managed soil had higher stocks between 10 and 30 cm depth. The higher OC content of this soil layer points towards ploughing-induced translocation of the organic amendments and/or increased leaching of OC originating from surface applied organic fertilizer, and possibly increased OC inputs due to a larger root biomass when compared to the conventional system. However, the highest total OC stock was found in the unmanaged meadow (169 t ha$^{-1)}$ which was part of the same field, indicating that there is significant potential for increasing or maintaining soil OC stocks via OC sequestration by plants. In the unmanaged meadow, the MAOM-C content of the uppermost 10 cm of the soil was nearly 60 g kg^{-1} and did not show signs of saturation which demonstrates a high potential of heavy clay soils (in here, > 530 g kg^{-1} of clay) for the OC accrual. In all of the studied management systems, the MAOM-C content of the surface soil was tightly related to the clay content, but deeper in the soil profile this relationship was not detected. Instead, in deeper soil layers both MAOM-C and POM-C were positively related to Al and Fe oxides, which indicates that oxides play a significant role in transporting and stabilizing OC in soils. This suggests that when estimating the OC accrual potential of deeper soil layers (below 40 cm) estimations should not be based on soil texture alone. Further, the slow rate of OC inputs reaching deeper soil layers and/or biogeochemical constraints preventing OC stabilisation may reduce the ability to increase subsoil OC stocks. However, at least some of the OC that enters the subsoil can potentially be retained for a long time.

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Data availability

Data will be made available on request.

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Appendix

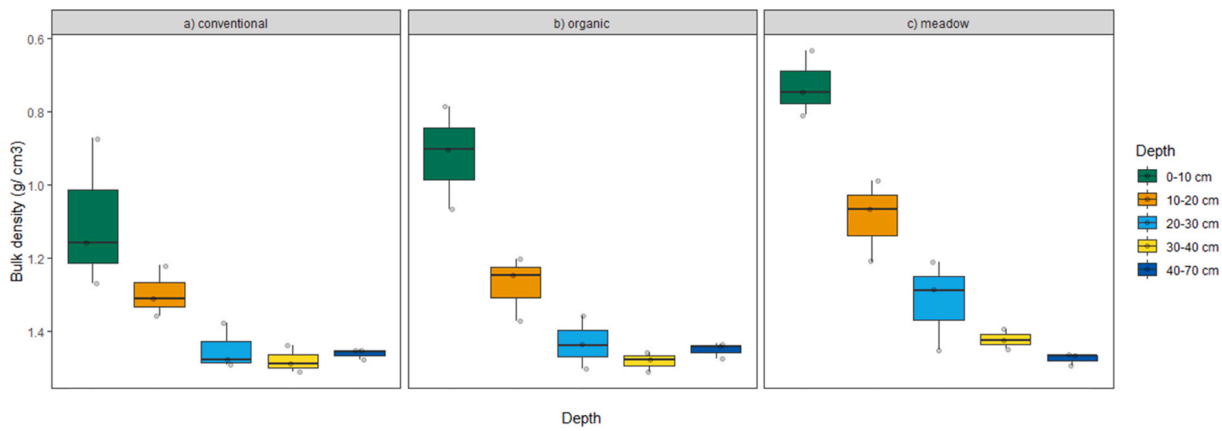

Fig. A1. Soil bulk densities (n = 3). No statistical differences between conventional and organic management.

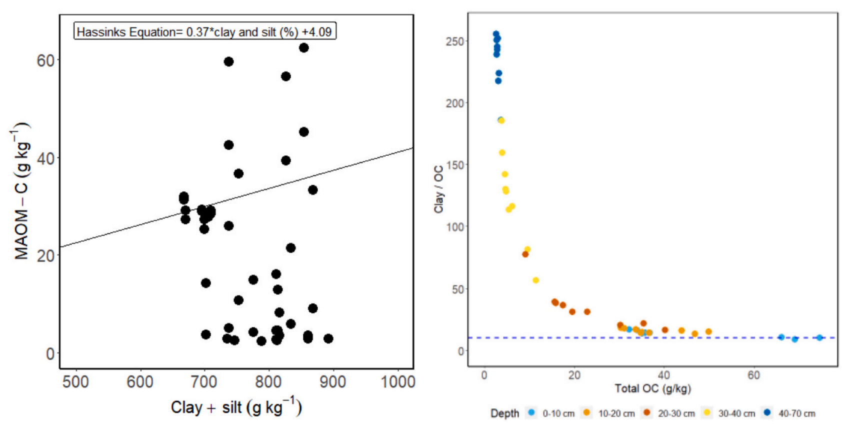

Fig. A2. Soil clay and silt content in relation to MAOM-C (g kg^{-1}) and the regression line of Hassink's Equation (left), and total soil OC in relation to clay to OC ratio (right).

Table A1
Proportions (%) of soil OC and sample mass in the MAOM and POM fractions. For all the studied soil layers, proportion of the total soil OC in the DOM was <0.032% (not shown in the table). No statistical differences were observed between conventional and organic management.

		Proportion of the total soil OC (%) in the fraction		Proportion of the sample mass (%) in the fraction	
Soil depth	Management	MAOM	POM	MAOM	POM
0–10 cm	Conventional	87 ± 2.0	13 ± 9.5	84 ± 1.9	16 ± 1.9
	Organic	83 ± 1.7	17 ± 10.5	84 ± 0.3	17 ± 0.3
	Meadow	85 ± 0.6	15 ± 9.2	86 ± 1.5	14 ± 1.5
10–20 cm	Conventional	85 ± 2.5	15 ± 10.7	83 ± 1.0	17 ± 1.0
	Organic	84 ± 1.3	16 ± 8.4	84 ± 1.2	16 ± 1.2
	Meadow	90 ± 0.2	10 ± 5.6	88 ± 2.3	12 ± 2.3
20–30 cm	Conventional	87 ± 3.9	13 ± 12.1	86 ± 3.2	14 ± 3.2
	Organic	85 ± 1.8	15 ± 7.3	87 ± 0.8	14 ± 0.8
	Meadow	93 ± 1.0	7 ± 5.2	88 ± 3.0	12 ± 3.0
30–40 cm	Conventional	95 ± 0.6	5 ± 3.3	93 ± 2.6	7 ± 2.6
	Organic	94 ± 1.0	6 ± 3.9	95 ± 1.3	5 ± 1.3
	Meadow	95 ± 0.6	5 ± 2.4	93 ± 2.2	7 ± 2.2
40–70 cm	Conventional	96 ± 0.3	4 ± 1.7	96 ± 1.1	4 ± 1.1
	Organic	97 ± 0.4	3 ± 1.5	96 ± 1.5	4 ± 1.5
	Meadow	93 ± 1.5	7 ± 3.7	95 ± 0.9	5 ± 0.9

Table A2
Average (±SE, $n = 9$) soil depths in which the Equal soil masses were fulfilled.

ESM t ha^{-1}	Management	Soil depth (cm)
1500	Conventional	14.5 ± 0.7
	Organic	15.2 ± 0.6
	Meadow	18.8 ± 0.5
3000	Conventional	25.9 ± 0.7
	Organic	26.8 ± 0.9
	Meadow	31.2 ± 0.7
7500	Conventional	57.0 ± 0.8
	Organic	58.0 ± 1.2
	Meadow	62.3 ± 0.8

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