

# Soil organic carbon fractions and storage potential in Finnish arable soils

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## Abstract

Understanding the factors affecting the total amount and distribution of soil organic carbon (OC) across different functional carbon pools is important to better define the future management of soil OC stocks. The interactions between soil management practices, local physicochemical soil properties and climate are essential for determining the OC content of the soil. Nevertheless, how these factors affect the total amount of OC and its distribution across carbon pools, i.e., more labile particulate (POC) and more stable mineral-associated (MAOC) organic carbon, is only partly known. In this study, we assessed topsoil (0–20 cm) samples from 93 arable farms in the southern half of Finland to determine the total amount of OC, and its distribution in MAOC and POC, along with relevant soil properties (amount of clay and silt, aluminium and iron oxides and pH), climate (precipitation and temperature) and fertilization (mineral versus organic). The fertilization did not affect the total soil carbon content (12–58 g OC kg<sup>-1</sup> soil). The share of OC in the MAOC fraction (on average 86% of total OC) was relatively stable across the large range of OC contents and clay contents (2%–68%). We assessed the highest feasible MAOC of the soils with boundary line analyses and their OC saturation state with Hassink's equation (Hassink, 1997). Only soils with the lowest clay content (<10% clay) were assumed to be carbon-saturated, suggesting that most of the studied soils have a capacity to accrue more MAOC. Simple linear regression showed that clay, aluminium and iron oxides explained 9%, 21% and 22% of the variation in MAOC, respectively. Multiple regression analyses including the amount of clay, clay+silt, aluminium and iron oxides, pH, type of fertilization, precipitation and temperature as explanatory variables explained 33%–53% of the variation in OC and MAOC. In all soils, aluminium oxides were important explanatory variable for MAOC, whereas Fe oxides were significant only in soils with higher clay content (>30%). In soils with a low clay content (<30%), pH had added value in explaining MAOC. Altogether, it seems that various climatic, edaphic and soil management-related factors are context-dependently

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controlling OC and that soil textural information alone is not necessarily an adequate predictor to assess the MAOC saturation state of the soil.

#### KEYWORDS

aluminium oxides, boundary line analyses, carbon saturation, clay, fertilizing, Hassink's equation, iron oxides, mineral-associated organic carbon, particulate organic carbon, soil texture

## 1 | INTRODUCTION

Soil organic matter (SOM) is recognized as a key for a multitude of soil functions (Hoffland et al., 2020; Wiesmeier et al., 2019), one of which, climate regulation, a potential sink for atmospheric carbon dioxide (CO<sub>2</sub>; Paustian et al., 2016) is receiving a lot of attention. Agricultural management has resulted in the depleted soil organic carbon (OC) globally (Paustian et al., 2016; Sanderman et al., 2017). There is now a strong focus on carbon farming practices which promote the incorporation of organic matter into soils as part of agricultural management to maintain or increase soil carbon stocks. However, to date, our mechanistic understanding of the soil processes relating to the soil OC dynamics and stabilization is still inadequate and results in variable outcomes in relation to carbon farming practices (Angst et al., 2023).

SOM is a complex mixture of organic molecules in different phases of decomposition (Schmidt et al., 2011) and hence presents in the soil in a multitude of forms (Simpson & Simpson, 2012). To determine the forms of SOM in the soil, it is often fractionated into mineral-associated (MAOM) and particulate (POM) organic matter (Cambardella & Elliott, 1992; Lavalley et al., 2020; Tiessen & Stewart, 1983). In mineral soils, the majority of OC is often present as mineral-associated organic carbon (MAOC; Kögel-Knabner et al., 2008, Georgiou et al., 2022) which is regarded as a relatively stable and long-lasting form of soil OC since its interactions with soil minerals guards it against further decomposition (Lavalley et al., 2020). In contrast, particulate organic carbon (POC) has only limited interaction with soil minerals and is hence considered more labile than MAOC, but soil aggregation or soil physicochemical status may still slow the rate of its decomposition (Lavalley et al., 2020). Around half of MAOC occurring in arable soils is presumed to be of microbial origin and half directly of plant origin (Angst et al., 2021) whereas POC comprises relatively undecomposed plant material (Lavalley et al., 2020).

MAOC is considered important from a climate mitigation perspective, as it potentially decomposes slower than POC and can form a relatively stable OC storage

#### Highlights

- Organic fertilization practices did not increase OC compared to mineral fertilization.
- A high proportion of OC in MAOC ( $86 \pm 3\%$ ) in soils that represented a large range of clay contents (2%–68%).
- The majority of studied soils have a capacity to accrue more MAOC.
- Detecting universally applicable predictors for soil OC is challenging.

(Lavalley et al., 2020). The more labile POC is used as an energy source for soil biota (Yu et al., 2022) which in turn also becomes a source for MAOC production (Angst et al., 2023). Approximately 20% of the OC content of arable soil is considered to be POC (Guillaume et al., 2022; Mayer et al., 2022; Sokol et al., 2022); however, the POC pool is considered to be dynamic which means its pool size can readily change as the result of soil management interventions. One of the soil management practices to which total OC, POC and MAOC may respond on a relatively short timescale is the type of fertilization applied (Angst et al., 2023). The application of organic fertilizers introduces OC in the form of POC into the soil, but depending on climatic and edaphic factors, most of the OC may decompose relatively soon after application (Maillard & Angers, 2014; Mayer et al., 2022), meaning that maintaining a certain level of soil OC stocks would require a continuous input of organic materials (Powlson & Neal, 2021). Decomposition of the added organic materials results in the respiration of some of the OC in the form of carbon dioxide (CO<sub>2</sub>) and therefore a loss of OC from the soil. The rate of this loss is dependent on the temperature, moisture and quality of the organic materials (Berthelin et al., 2022; Powlson & Neal, 2021). However, this process also results in the assimilation of soil organic carbon into the microbial biomass, and this biologically processed OC contributes to a relatively higher proportion of OC in the MAOC fraction (Angst et al., 2021).

The long-term stabilization of OC in the form of MAOC is proposed to be strongly dependent on soil properties such as mineral particles and various metal oxides, and soil pH (Rasmussen et al., 2018; Wiesmeier et al., 2019). The amount of clay-sized (<2  $\mu\text{m}$ ) and silt (<20  $\mu\text{m}$  or <60  $\mu\text{m}$ ) particles has traditionally been considered an adequate predictor of the soil OC storing capacity (Dexter et al., 2008; Feng et al., 2013; Wiesmeier et al., 2019) as the proportion of these particles provides a reference of mineral surface area available for MAOC binding. Furthermore, clay is a paramount factor in soil aggregation which may hinder further OC decomposition as aggregates often form around POC particles, making it physically inaccessible for decomposer organisms (Besnard et al., 1996; Totsche et al., 2018). However, despite the acknowledged importance of the clay-sized soil minerals for OC storage, it remains unclear what the limitations are for the maximum binding capacity for MAOC on these mineral surfaces, and some studies find no upper limit for the operationally defined MAOC (Begill et al., 2023; Matus, 2021; Salonen et al., 2023; Urbanski et al., 2023).

Finnish soils are relatively young as they were formed by Weichselian glaciation around 10,000 years ago (Koljonen, 1992). During the glaciation, soils and their clay and silt-size minerals were formed from rock by abrasion of the ice. The felsic parent material (Yli-Halla & Mokma, 2002) from which these soils are formed is strongly durable and resistant to in-situ weathering, leading to a relatively large proportion (more than 50%; Keskinen et al., 2022) of the minerals in the clay and silt-sized fractions of Finnish soils being only moderately weathered. This means that they have a relatively low surface activity in comparison to soils that are further weathered and hence containing a larger share of 1:1 or 2:1 type of clay minerals that are important in stabilizing soil OC (Georgiou et al., 2022; Six et al., 2002; Six et al., 2024).

As soil mineralogy is spatially variable, so are the associated surface properties such as charge density and surface area (Mitchell & Soga, 2005) and soils with corresponding clay+silt content may have differing types of mineral surfaces. Therefore, the surface activity and MAOC storage capacity may be different despite a similar clay+silt content (Feng et al., 2013; Georgiou et al., 2022). Different metrics applying the amount of specific-sized soil minerals (i.e., clay and/or silt) or the type of the dominating clay mineral (i.e., 1:1 or 2:1) can be used to assess the OC saturation state of soil and to estimate OC accrual potential of soil (e.g., Dexter et al., 2008; Feng et al., 2013; Georgiou et al., 2022; Hassink, 1997; Schjøning et al., 2012; Six et al., 2024). Estimating the soil OC saturation state can provide information on the OC sequestration potential of agricultural soils, which can be

potentially useful from the climate mitigation perspective since soils can act as a carbon sink (Keenan & Williams, 2018; Paustian et al., 2016).

In addition to clay and silt, oxides of aluminium (Al) and iron (Fe) can act efficiently as OC binding agents (Hall & Thompson, 2022; Mendez et al., 2020; Wiesmeier et al., 2019; Wiseman & Püttmann, 2006). Interaction of OC with Al and Fe can include OC adsorption onto oxide surfaces, strong inner-sphere bond formation between OC and Al and Fe oxides, and co-precipitation of OC and oxides (Gerke, 1992; Schneider et al., 2010; Tamrat et al., 2019). Their oxalate-extractable species (Al oxides and Fe oxides) have been shown to be better predictors for soil OC than soil texture (i.e., clay or clay+silt content) in soils of humid cold climates with relatively low pH (Fukumasu et al., 2021; Rasmussen et al., 2018; Salonen et al., 2023; Wiesmeier et al., 2019). Such soils are typical of boreal conditions in Finland (Metzger et al., 2012) where relatively cold mean annual temperatures hinder evapotranspiration, leading to prevalent moist conditions that can hamper SOM decomposition (Wiesmeier et al., 2019) and that may lead to relatively low soil pH which may further retard microbial decomposition of soil carbon (Keiluweit et al., 2016; Slessarev et al., 2016).

Our objectives were: (i) to assess the amount of OC and its distribution across MAOC and POC carbon fractions in arable soils receiving organic or mineral fertilization; (ii) to estimate the OC saturation state of the studied soils; (iii) to assess which soil properties (clay, silt, Al and Fe oxides, and pH) explain the different proportions of the carbon fractions; and (iv) to determine whether climatic factors, that is, precipitation and temperature, control the total amount of OC and its distribution into MAOC and POC. We analysed topsoil (0–20 cm) samples from 93 farms with varying soil textures (clay content 2%–68%) located across the southern half of Finland (60°N–65°N) for the total amount of OC and its distribution between MAOC and POC. We used a boundary line analysis (Feng et al., 2013; Georgiou et al., 2022; Six et al., 2024) to assess the highest feasible MAOC values for these soils under the current agricultural management. Further, the MAOC saturation state of the soil was assessed with Hassink's equation (Hassink, 1997). We hypothesized that: (1) there will be higher levels of total OC, MAOC and POC in organically fertilized soils due to higher inputs of organic matter; (2) as cultivation often depletes soil OC stocks, the studied soils will not be OC-saturated; (3) Al and Fe oxides will be better predictors of MAOC than clay content as they act as the preferential binding sites; and (4) soil OC concentration increases with increasing precipitation and decreases with increasing temperature.

## 2 | MATERIALS AND METHODS

### 2.1 | Soil sampling and basic soil characterization

Soil samples were collected during the years 2018 and 2019 right after establishing the Finnish Carbon Action project (Mattila et al., 2022) focussing on the effects of a range of soil management practices that are estimated to have the potential to increase soil OC levels. At the start, participating farmers selected a field within their farm for the project and reported its soil management history for the 5 years preceding the start and baseline soil sampling (i.e., for the years 2014–2018 or 2015–2019, depending on the year that the farm entered the project). Studied soils were in arable use and there were no permanent grasslands included. Most of the farms had cereals ( $n = 78$ ) and grasses ( $n = 52$ ) included in the five-year crop rotation before the soil sampling. Based on the soil management history from 5 years before the soil sampling, the studied farms were divided into two groups: farms applying mainly mineral fertilizers and

farms applying mainly organic fertilization. The quality and amounts of applied fertilizing (in both, farms that applied mineral and organic fertilizing) varied from farm to farm, considering that the applied maximum amounts of nutrients were in line with the national regulations. Individual rates of the amounts of nutrients applied with fertilizing were not available. Despite the nature of the data (i.e., only a 5-year period prior to sampling had been considered and lack of the quantities of OC applied with the organic fertilizing), we decided to divide the farms into minerally and organically fertilized farms to assess whether effects of fertilization could be seen in the total OC, or its distribution between the MAOM and POM fractions. The farms were located across the southern half of Finland ( $60^{\circ}\text{N}$ – $65^{\circ}\text{N}$ ; Figure 1). Long-term mean annual precipitation (MAP) in the studied farms was 636 mm, with a median of 631 mm (range 548–727 mm year<sup>-1</sup>). Long-term mean annual temperature (MAT) was  $5.1^{\circ}\text{C}$ , with a median of  $5.2^{\circ}\text{C}$  (range of  $3.3$ – $6.4^{\circ}\text{C}$ ). MAP and MAT are 19-year averages before the soil sampling (years 1998–2017; Finnish Meteorology Institute. Data from the weather stations closest to each farm).

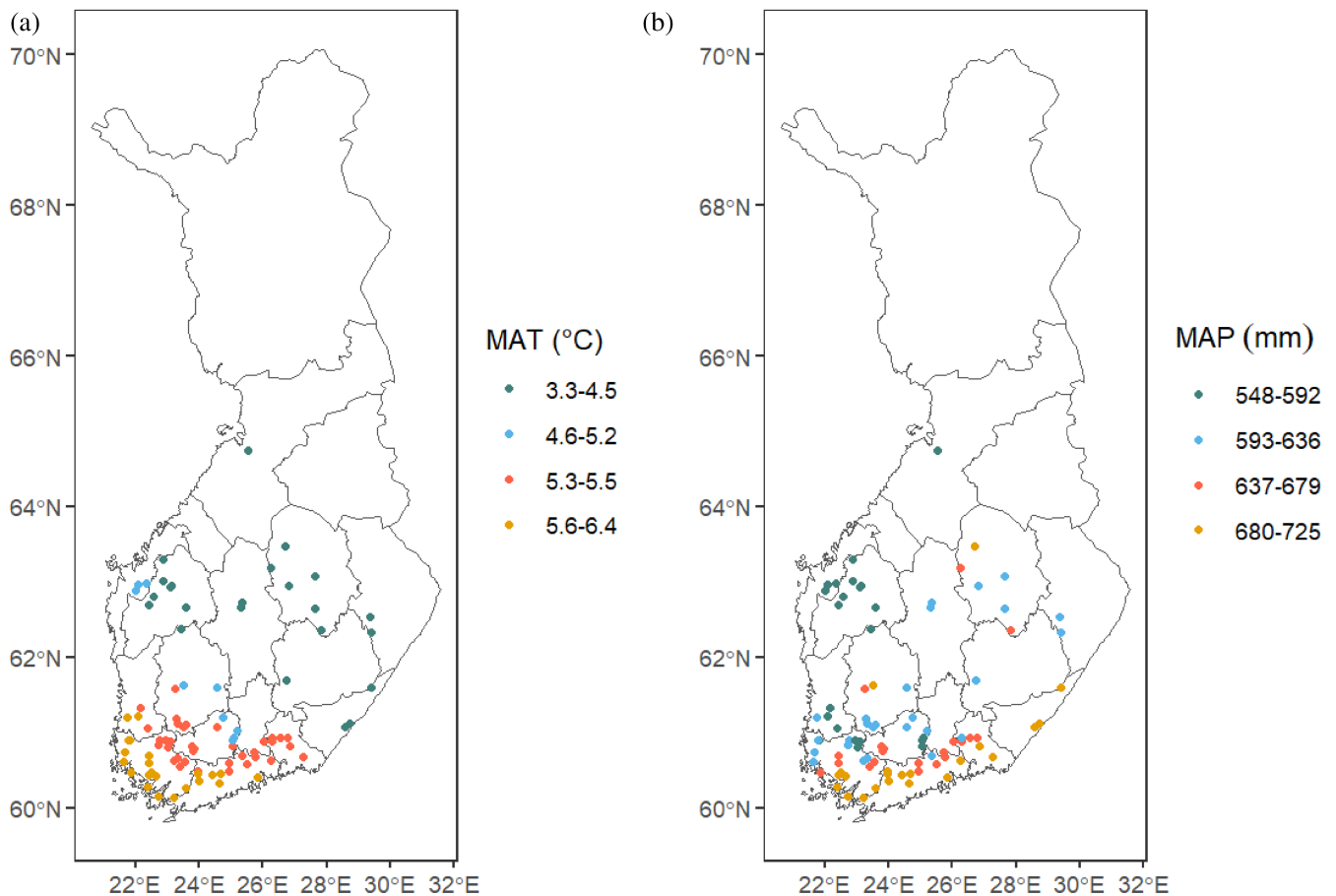


FIGURE 1 Locations of the studied farms in Finland and mean annual temperature (1A, MAT,  $^{\circ}\text{C}$ ) and precipitation (1B, MAP, mm). MAT and MAP are 19-year averages.

The samples analysed in this study were taken from three geo-referenced sampling points per field as part of the baseline sampling. Baseline sampling took place in the autumn of the start year, after the last harvest, before the carbon farming practices were commenced. The top-soil (0–20 cm) was sampled by the participating farmers who collected 10 soil core ( $\varnothing$  14 mm) samples on the circumference of a 10-m radius circle. The 30 samples were bulked to form one composite sample which was sent in a plastic container by a courier service to the University of Helsinki (Helsinki, Finland), all samples arrived within 3 days of sampling. Soils were sieved (mesh size 10 mm) and part of the samples were stored at  $-20^{\circ}\text{C}$  prior pending further analyses, and the other part was analysed for elemental C and N (LECO, Michigan, USA).

## 2.2 | MAOM and POM fractionation, Al and Fe oxide extraction, and soil textural analyses

Soils were fractionated by size into MAOM ( $<53\ \mu\text{m}$ ) and POM ( $>53\ \mu\text{m}$ ) according to Cotrufo et al. (2019). In short, frozen soils (stored at  $-20^{\circ}\text{C}$  prior to the analyses) were melted at  $+4^{\circ}\text{C}$ , sieved (mesh size 2 mm) and air-dried. Then the soil samples were dispersed by shaking in  $5\ \text{g l}^{-1}$  sodium hexametaphosphate and glass beads for 18 h at 120 rpm (Ika LabortechnikKS 501 digital). After the dispersion, the soil was rinsed on a sieve (mesh size  $53\ \mu\text{m}$ ). The soil that passed through the sieve was collected as MAOM ( $<53\ \mu\text{m}$ ), and the soil on top of the sieve was collected as POM ( $>53\ \mu\text{m}$ ). Fractions were dried to a constant weight in a forced-air oven ( $60^{\circ}\text{C}$ ). To confirm reproducibility of the soil dispersion, two internal reference soils (clay- and coarse-textured soil) were included in each set of fractionated soils. Samples were analysed for OC (MAOC and POC) by dry combustion (LecoCHN 628, St. Joseph, Michigan, USA). OC recovery was on average 97% and ranged from 100 to 84%. All the measured C was taken to represent OC as due to the inherently low pH in Finnish soils, carbonate minerals are absent (Nelson & Sommers, 1982).

Poorly crystalline Al and Fe oxides were extracted with acid ammonium oxalate extraction according to Niskanen (1989; 0.05 M oxalate, pH 3.3). Prior to the analysis, soil was stored at  $-20^{\circ}\text{C}$ , then defrosted to  $+4^{\circ}\text{C}$ , sieved (mesh size 2 mm) and air-dried. We used 5 g of air-dried soil in the extraction. Al and Fe were measured with inductively coupled plasma optical emission spectrometry (ICP-OES Thermo Scientific iCAP 6300 MFC DUO).

Soil texture (size classes: clay  $<2\ \mu\text{m}$ ; fine silt 2–20  $\mu\text{m}$ ; coarse silt 20–60  $\mu\text{m}$ ; fine sand 60–200  $\mu\text{m}$ ; and

coarse sand  $>200\ \mu\text{m}$ ) was analysed with the pipette method (Elonen, 1971). Following the protocol, soils were pre-treated with  $\text{H}_2\text{O}_2$  for SOM removal and then acidified with 2 M HCl and dispersed with 0.05 M  $\text{Na}_4\text{P}_2\text{O}_7$ .

## 2.3 | Estimations of soil OC saturation and OC accrual potential

We applied a modified boundary line analysis to estimate the maximum capacity for MAOC stabilization (as in Feng et al., 2013, Georgiou et al., 2022, Six et al., 2024). In the boundary line analyses, the soils having the highest MAOC contents were used in analysing a feasible maximum for OC accrual in the studied climate and under the current arable land management. For the analysis, data were sorted by mass proportions of clay+silt ( $<60\ \mu\text{m}$ ) particles in bulk soil ( $\text{g kg}^{-1}$  soil) and then separated into groups with intervals of 100 g of the clay+silt fraction  $\text{kg}^{-1}$  soil. Next, the upper tenth percentile of the MAOC content of clay+silt particles in each group was identified and then the upper tenth percentile of the MAOC contents of clay+silt particles and the corresponding mass proportions from each group were combined and used in a regression analysis where the intercept was forced through zero. We then used the slope from the boundary line analyses (Figure 2) to estimate the highest feasible MAOC content ( $\text{g OC kg}^{-1}$  clay+silt) for the studied soils as follows (Table 2): Maximum

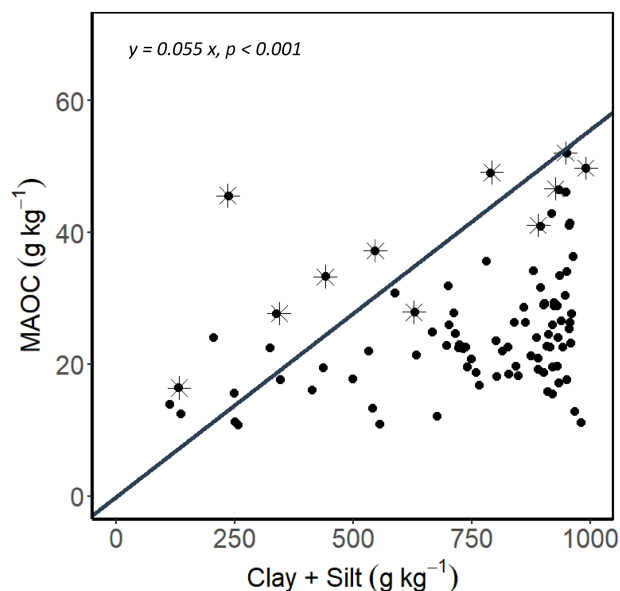


FIGURE 2 Prediction of the maximal MAOC content of clay+silt ( $<60\ \mu\text{m}$ ). Regression is based on boundary line analyses with the data of the upper tenth percentile of MAOC contents included within clay+silt 100  $\text{g kg}^{-1}$  soil intervals (marked with asterisks).

MAOC = clay+silt content (%) × maximum MAOC for the studied soils (55 g C kg<sup>-1</sup> silt+clay). We also estimated the maximum MAOC for the studied soils assuming 2:1 or 1:1 clay mineral dominated (Six et al., 2024) as follows: Maximum MAOC = clay+silt content (%) × maximum MAOC for 1:1 (46 g C kg<sup>-1</sup> silt+clay) or 2:1 (82 g C kg<sup>-1</sup> silt+clay).

Soil texture was used to estimate the MAOC accrual capacity for each soil (Table 2). We calculated the capacity of fine-sized particles to stabilize MAOC using the Hassink's (1997) equation: MAOC (g kg<sup>-1</sup>) at OC saturation = 4.09 + 0.370 × (clay+silt%). For clay and silt, we used two size cut-offs: clay+silt <20 μm, as in Hassink, 1997, and clay+silt <60 μm. Larger clay+silt (<60 μm) was included as it is suggested that minerals up to this size have relevant specific surface area for MAOC binding (Six et al., 2024). These accrual capacity estimations were compared with measured MAOC to assess the potential for further MAOC accrual of the soils. Further, we divided soils into saturated and non-saturated according to Hassink's equation (with clay+silt size cut-off <20 μm) to test the effect of fertilizing on the distribution of soil OC into MAOC and POC (Table 3).

## 2.4 | Data analyses

Out of the 105 farms participating in the Carbon Action project, soil samples from 97 were available for our analyses. Among these 97 farms, there were four soils that were classified as highly organic (OC >7%, OM 12%–20%; Paasonen-Kivekäs et al., 2009) according to the Finnish soil classification system. As these highly organic soils had considerably higher OC content than the rest of the studied soils, we excluded them from the statistical analyses, leaving 93 soils for a part of the statistical analyses.

For three out of the remaining 93 farms, details on the fertilization history were not available (not reported by farmers) and hence these three farms were also excluded from the statistical analyses where fertilization (mineral vs organic) was assessed. The remaining 90 farms were divided into two groups based on their fertilization history (mineral,  $n = 46$  and organic,  $n = 44$ ). Two-way ANOVA with a Tukey HSD test (package 'stats') was conducted to evaluate statistical differences between OC and nitrogen (N) concentrations and OC to N ratios of total soil, MAOM and POM, OC contents of MAOM and POM, soil pH, and clay+silt content (%; <60 μm) in mineral and organically fertilized soils grouped by clay content (0–100, 100–200, 200–300 g clay kg<sup>-1</sup>soil etc.). Division to the clay content groups was chosen as some studies have reported increasing OC content with increasing clay content (Arrouays et al., 2006; Hassink, 1997; Kaiser & Guggenberger, 2003).

Further, to assess whether fertilization (mineral vs. organic) would yield different outcomes depending on the soil OC saturation state, we divided soils into two groups: MAOC-saturated and non-saturated. We then employed a *t*-test (using the 'rstatix' package; Kassambara, 2022) to evaluate differences in OC and N contents.

We performed a multiple linear regression to identify predictors for soil OC and MAOC. The selection of the best explanatory variables was performed on an AIC-driven model selection approach ('dredge' function from the package MuMIn Bartoń, 2023). As explanatory variables, we used textural class (clay <2 μm or clay+silt <60 μm) (g kg<sup>-1</sup> soil; see details below), amount of Al and Fe oxides (g kg<sup>-1</sup> soil), pH, cumulative annual rainfall (mm; yearly average from the 19-year time period 1998–2017), mean annual temperature (°C; yearly average from 19-year time period 1998–2017) and fertilization (mineral vs. organic fertilizers). We divided soils into two groups according to their clay content: (1) <30% of clay and (2) >30% of clay. The 30% cut-off was chosen as according to the Finnish soil classification system clay soil has >30% of clay (Paasonen-Kivekäs et al., 2009). The variance inflation factor for the covariates of the models was checked using the 'vif' function of the car package (Fox & Weisberg, 2019) and this was found to be <2, meaning that no co-linearity of the covariates of the best-fit models was observed. We inspected the distribution of the residuals of the final models visually to check that model assumptions were not violated.

All statistical analyses were performed with R (R Core Team, 2023, version 4.3.1), and all the plots were created using R packages 'ggplot2' and 'ggpubr' (Kassambara, 2020; Wickham et al., 2016). We regarded *p*-values of 0.05 or less as statistically significant.

## 3 | RESULTS

### 3.1 | MAOC and POC across clay contents

Soil OC and N contents (g kg<sup>-1</sup> soil) tended to increase with increasing clay content, with the exception of the clay content interval of 200–300 g kg<sup>-1</sup> which had less OC than the previous clay intervals, and the clay interval of 300–400 g kg<sup>-1</sup> that had the highest measured OC content (Table 1). N contents were significantly higher in soils having >400 g kg<sup>-1</sup> clay than in soils that contained less clay. OC content (C%) of the <53 μm soil fraction (i.e., MAOM) was highest in the lowest clay content interval (0–100 g kg<sup>-1</sup>, *p*-value <0.05). In contrast, the OC content (C%) of the >53 μm soil fraction (i.e., POM) increased with increasing clay content.

**TABLE 1** Average ( $\pm$ SE) organic carbon and nitrogen concentration ( $\text{g kg}^{-1}$  soil) of total soil, the C to N ratio (C:N) of total soil, MAOM ( $<53 \mu\text{m}$  soil) and POM ( $>53 \mu\text{m}$  soil), the OC concentration ( $\text{g kg}^{-1}$  soil) and contents (%) of MAOC and POC in the  $<53$  and  $>53 \mu\text{m}$  soil mass fraction, respectively, and soil pH in different clay classes by  $100 \text{ g kg}^{-1}$  intervals.

Clay ( $\text{g kg}^{-1}$ )	<i>n</i>	Total OC ( $\text{g kg}^{-1}$ )		Total N ( $\text{g kg}^{-1}$ )		MAOM ( $<53 \mu\text{m}$ soil) C-%		MAOC ( $\text{g kg}^{-1}$ soil)		MAOM C:N		POM ( $>53 \mu\text{m}$ soil) C-%		POC ( $\text{g kg}^{-1}$ soil)		POM C:N		pH		
0–100	14	24.3 $\pm$ 3.1 <sup>ab</sup>	1.90 $\pm$ 0.16 <sup>a</sup>	18 $\pm$ 0.9 <sup>a</sup>	7.1 $\pm$ 0.9 <sup>a</sup>	20.2 $\pm$ 2.7 <sup>ab</sup>	18 $\pm$ 1.0 <sup>a</sup>	0.7 $\pm$ 0.1 <sup>a</sup>	4.1 $\pm$ 0.6	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	18 $\pm$ 1.1 <sup>a</sup>	6.43 $\pm$ 0.19	6.43 $\pm$ 0.19
100–200	12	29.0 $\pm$ 3.6 <sup>ab</sup>	1.90 $\pm$ 0.16 <sup>a</sup>	15 $\pm$ 0.8 <sup>b</sup>	4.0 $\pm$ 0.6 <sup>b</sup>	25.3 $\pm$ 3.2 <sup>ab</sup>	14 $\pm$ 0.8 <sup>b</sup>	1.8 $\pm$ 0.4 <sup>a</sup>	3.7 $\pm$ 0.5	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	20 $\pm$ 1.6 <sup>ab</sup>	6.38 $\pm$ 0.15	6.38 $\pm$ 0.15
200–300	12	22.6 $\pm$ 1.4 <sup>a</sup>	1.69 $\pm$ 0.09 <sup>a</sup>	13 $\pm$ 0.5 <sup>b</sup>	2.6 $\pm$ 0.3 <sup>b</sup>	18.7 $\pm$ 1.3 <sup>a</sup>	13 $\pm$ 0.4 <sup>b</sup>	2.5 $\pm$ 0.5 <sup>ab</sup>	3.9 $\pm$ 0.8	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	21 $\pm$ 1.4 <sup>ab</sup>	6.33 $\pm$ 0.12	6.33 $\pm$ 0.12
300–400	23	33.9 $\pm$ 2.3 <sup>b</sup>	2.24 $\pm$ 0.11 <sup>ab</sup>	15 $\pm$ 0.4 <sup>b</sup>	3.4 $\pm$ 0.2 <sup>b</sup>	29.3 $\pm$ 2.1 <sup>b</sup>	14 $\pm$ 0.4 <sup>b</sup>	5.4 $\pm$ 0.9 <sup>b</sup>	4.6 $\pm$ 0.4	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	22 $\pm$ 0.7 <sup>ab</sup>	6.38 $\pm$ 0.09	6.38 $\pm$ 0.09
400–500	8	31.1 $\pm$ 3.4 <sup>ab</sup>	2.35 $\pm$ 0.33 <sup>b</sup>	14 $\pm$ 0.6 <sup>b</sup>	3.3 $\pm$ 0.4 <sup>b</sup>	27.8 $\pm$ 3.3 <sup>ab</sup>	13 $\pm$ 0.6 <sup>b</sup>	3.5 $\pm$ 0.8 <sup>ab</sup>	3.4 $\pm$ 0.3	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	22 $\pm$ 2.0 <sup>ab</sup>	6.24 $\pm$ 0.13	6.24 $\pm$ 0.13
500–600	12	30.1 $\pm$ 1.2 <sup>ab</sup>	2.20 $\pm$ 0.06 <sup>b</sup>	14 $\pm$ 0.4 <sup>b</sup>	3.0 $\pm$ 0.1 <sup>b</sup>	26.2 $\pm$ 1.2 <sup>ab</sup>	13 $\pm$ 0.4 <sup>b</sup>	3.9 $\pm$ 0.9 <sup>ab</sup>	3.9 $\pm$ 0.5	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	22 $\pm$ 0.5 <sup>ab</sup>	6.35 $\pm$ 0.10	6.35 $\pm$ 0.10
600–700	12	32.6 $\pm$ 2.7 <sup>ab</sup>	2.45 $\pm$ 0.2 <sup>b</sup>	13 $\pm$ 0.4 <sup>b</sup>	3.1 $\pm$ 0.3 <sup>b</sup>	28.0 $\pm$ 2.4 <sup>ab</sup>	12 $\pm$ 0.3 <sup>b</sup>	5.8 $\pm$ 0.6 <sup>b</sup>	4.5 $\pm$ 0.7	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	23 $\pm$ 1.1 <sup>b</sup>	6.40 $\pm$ 0.11	6.40 $\pm$ 0.11

Note: Letters denote statistical differences (Tukey's HSD, significance level  $<0.05$ ). Clay and silt contents were not tested for statistical differences, *n* = number of farms sampled (in total *n* = 93). The horizontal line between the clay classes of 200–300  $\text{g kg}^{-1}$  and 300–400  $\text{g kg}^{-1}$  indicates the cut-off between low clay ( $<30\%$ ) and high clay ( $>30\%$ ) soils.

The proportion of the total OC in the MAOM fraction varied between 83% and 89% (Table S1). The total amount of MAOC expressed per  $\text{g OC kg}^{-1}$  total soil was lowest in the clay content interval of 200–300  $\text{g kg}^{-1}$  and tended to be different in the soils with differing clay contents whereas the total amount of POC expressed per  $\text{g OC kg}^{-1}$  total soil did not differ between the clay classes. The bulk soil C to N ratio in the different clay classes was 15 on average (Table 1), and a significantly higher ratio (C to N ratio = 18) was observed in the 0–100  $\text{g kg}^{-1}$  clay content interval compared to the soils with a higher clay content (C to N ratio = 13–15). Such a decrease in C to N ratio with increasing soil clay content was found also for MAOM (decrease from C to N ratio 18 to 12) but not for POM, where the C to N ratio increased from 18 to 23. No statistically significant differences were observed in soil pH between the different clay content intervals.

There were no statistically significant differences observed in the carbon- and nitrogen-associated parameters across the clay content intervals for either mineral or organically fertilized sites (Table S2).

### 3.2 | The OC saturation status of the soils under current agricultural management

With the boundary line analyses, the estimated feasible practical maximum MAOC in the studied climate and under the current agricultural management was 55  $\text{g MAOC kg}^{-1}$  clay+silt (Figure 2).

The estimated feasible highest possible MAOC contents based on the boundary line analyses were higher than the estimates assuming 1:1 clay mineral dominated soils (46  $\text{g OC kg}^{-1}$  clay+silt; Six et al., 2024) and lower than when estimated for 2:1 clay mineral dominated soils (82  $\text{g OC kg}^{-1}$  clay+silt). Only the soils in the lowest clay content interval (0–100  $\text{g kg}^{-1}$ ) reached their MAOC saturation according to the boundary line analyses as they contained 118% of the estimated feasible MAOC whereas the other clay content intervals contained 45%–66% of the estimated feasible MAOC.

To critically assess the results of the boundary line analysis, we applied Hassink's equation (Hassink, 1997) for verification. When the MAOC saturation was estimated based on Hassink's equation (Hassink, 1997) including a clay+silt fraction sized  $<20 \mu\text{m}$ , the MAOC accrual capacities were exceeded in the low clay soils (0–100 and 100–200  $\text{g clay kg}^{-1}$  soil; Table 2). However, when including also the larger silt fraction (clay+silt  $<60 \mu\text{m}$ ), only soils in the lowest clay content interval (0–100  $\text{g clay kg}^{-1}$  soil) were estimated to be carbon-saturated, and soils with a clay content  $>100 \text{ g kg}^{-1}$  were

**TABLE 2** Clay (%; <2 µm) and clay+silt content (%; <20 µm and <60 µm) of the soils, estimated maximum MAOC (g OC kg<sup>-1</sup> soil) according to Hassink's equation (with clay+silt size cut-offs <20 µm and <60 µm), and maximum OC accrual estimates by boundary line analyses (g OC kg<sup>-1</sup> clay+silt <60 µm) for 1:1 and 2:1 clay mineral dominated soils, and estimated feasible MAOC (g MAOC kg<sup>-1</sup> clay+silt) in the studied soils under current agricultural management in different clay classes by 100 g kg<sup>-1</sup> intervals.

Clay (g kg <sup>-1</sup> )	Clay (<2 µm) %	Clay + silt (<20 µm) %	Clay + silt (<60 µm) %	Total OC (g kg <sup>-1</sup> soil)	MAOC (g k <sup>-1</sup> soil)	Hassink's equation		Estimated maximum OC content with boundary line analyses		Current MAOC from the estimated feasible MAOC in own soils			
						Estimated maximum (g OC kg <sup>-1</sup> soil)	MAOC from estimated maximum (%)	Clay+silt <20 µm	Clay+silt <60 µm		Dominated clay mineral		
											1:1 (g OC kg <sup>-1</sup> clay+silt)	2:1 (g OC kg <sup>-1</sup> clay+silt)	
0–100	5 ± 0.6	15 ± 1.7	31 ± 4.5	24.3 ± 3.1 <sup>ab</sup>	20.2 ± 2.7 <sup>ab</sup>	9.5 ± 0.6	213 ± 27.4 <sup>a</sup>	15.6 ± 1.7	130 ± 20.4 <sup>a</sup>	14	26	17	118
100–200	15 ± 0.8	43 ± 4.2	70 ± 5.4	29.0 ± 3.6 <sup>ab</sup>	25.3 ± 3.2 <sup>ab</sup>	20.1 ± 1.6	126 ± 21.6 <sup>b</sup>	30.2 ± 2.0	84 ± 12.9 <sup>b</sup>	32	59	39	66
200–300	24 ± 0.6	64 ± 5.1	76 ± 5.2	22.6 ± 1.4 <sup>a</sup>	18.7 ± 1.3 <sup>a</sup>	27.6 ± 1.9	68 ± 8.2 <sup>b</sup>	32.1 ± 1.9	58 ± 6.7 <sup>b</sup>	35	64	42	45
300–400	36 ± 0.5	75 ± 2.4	87 ± 2.2	33.9 ± 2.3 <sup>b</sup>	29.3 ± 2.1 <sup>b</sup>	32.0 ± 0.9	92 ± 5.8 <sup>b</sup>	36.2 ± 0.8	81 ± 4.9 <sup>b</sup>	40	73	48	61
400–500	46 ± 1.0	77 ± 3.9	85 ± 3.5	31.1 ± 3.4 <sup>ab</sup>	27.8 ± 3.3 <sup>ab</sup>	32.4 ± 1.4	86 ± 10.4 <sup>b</sup>	35.5 ± 1.3	78 ± 9.1 <sup>b</sup>	39	71	47	59
500–600	55 ± 0.8	80 ± 2.6	85 ± 2.8	30.1 ± 1.2 <sup>ab</sup>	26.2 ± 1.2 <sup>ab</sup>	33.6 ± 1.0	78 ± 3.6 <sup>b</sup>	35.7 ± 1.0	73 ± 2.8 <sup>b</sup>	39	71	47	56
600–700	62 ± 0.6	85 ± 1.1	92 ± 0.9	32.6 ± 2.7 <sup>ab</sup>	28.0 ± 2.4 <sup>ab</sup>	35.7 ± 0.4	78 ± 7.2 <sup>b</sup>	38.0 ± 0.3	74 ± 6.2 <sup>b</sup>	42	77	51	55

Note: Letters in MAOC from estimated maximum with Hassink's equation denote statistical differences (Tukey's HSD, significance level <0.05), *n* = number of farms sampled. Other variables were not tested for statistical differences. The horizontal line between the clay classes of 200–300 g kg<sup>-1</sup> and 300–400 g kg<sup>-1</sup> indicates the cut-off between low clay (<30%) and high clay (>30%) soils.



found to be below their estimated saturation level. In the >200 g clay kg<sup>-1</sup> soils, the estimated maximum MAOC saturation capacity was not observed.

When we divided the soils into carbon-saturated and non-saturated soils according to Hassink's equation (with clay+silt size cut-off <20 µm; Table 3), we observed no fertilization (mineral vs. organic) related differences (*t*-test) in carbon- and nitrogen-associated soil parameters within the saturated or non-saturated soils.

### 3.3 | Soil properties, climate and fertilization regime as explanatory variables of total OC and its distribution into MAOC and POC

When observing all the studied soils together (clay content 2%–68%), clay content strongly correlated with the concentration of Fe oxides. While Al oxides did not significantly correlate with clay content, there was a significant correlation between Al and Fe oxides concentration (Table 4). Likewise, in the clay <30% soils, clay and Fe oxides correlated strongly whereas in clay >30% soils, Fe oxides and clay did not correlate but Al oxides and clay, as well as Fe oxides and Al oxides correlated.

For total OC and MAOC, simple linear regression analyses for all soils together showed positive relationships with clay, Al and Fe (*p*-values <0.05; Figure 3). There was a significant positive relationship between soil clay content and total OC and MAOC (*p* = 0.005 for both), which accounted for 9% of the variation in the carbon data. Al and Fe oxides accounted for more of the variation, describing around 21%–23% of the variation in total OC and MAOC. Neither clay nor Al and Fe oxides explained variation in POC.

Multiple regression models explained 33%–50% of the variation in total OC and 36%–53% of the variation in MAOC (Table 5). Yearly annual temperature (°C) was not chosen as an explanatory variable in any of the models, nor was the clay content (g kg<sup>-1</sup> soil), whereas clay+silt content (g kg<sup>-1</sup> soil) was a significant explanatory variable in the total OC and MAOC models (*p*-value <0.001; Table 5, Table S3). Al oxide was the only explanatory parameter that contributed (*p*-value <0.05) to the explanation of variance in all models, whereas Fe oxides were not included in the models for soils with low (<30%) clay content for both total OC and MAOC. Instead, pH was important in explaining total OC and MAOC in the clay <30% soils.

Generally, best-fit models explaining total OC and MAOC per clay content class (< or >30% clay) were very similar. The only deviation between the models was that mean annual precipitation (MAP) was not a significant

TABLE 3 Soil organic carbon properties and pH of soils are divided according to the MAOC saturation level (saturated and non-saturated, respectively, according to Hassink's equation with clay+silt size cut-off <20 µm) and fertilizer application.

MAOC saturation state of the soil	Fertilization	<i>n</i>	Total OC (g kg <sup>-1</sup> )	Total N (g kg <sup>-1</sup> )	Soil CN	MAOC (g kg <sup>-1</sup> soil)	MAOM (<53 µm soil) C-%	MAOM CN	MAOM (>53 µm soil) C-%	POM CN	POM	pH	Clay %	Clay+silt %	Al-ox (g kg <sup>-1</sup> soil)	Fe-ox (g kg <sup>-1</sup> soil)	Mean Hassink saturation (%)
Saturated	Mineral	16	32 ± 4	2.0 ± 0.2	16 ± 0.6	28 ± 3.2	4.9 ± 0.6	16 ± 0.6	3.7 ± 0.5	2.6 ± 0.8	18 ± 1.2	6.4 ± 0.1	25 ± 5	65 ± 7	1.9 ± 0.2	4.1 ± 0.6	145
	Organic	19	35 ± 3	2.2 ± 0.2	17 ± 0.7	30 ± 2.9	6.1 ± 0.7	16 ± 0.8	4.4 ± 0.3	3.4 ± 1.1	21 ± 1.1	6.2 ± 0.1	22 ± 4	56 ± 7	2.5 ± 0.2	4.0 ± 0.6	179
Non-saturated	Mineral	30	27 ± 1	2.0 ± 0.1	14 ± 0.2	23 ± 0.9	2.8 ± 0.1	13 ± 0.2	4.3 ± 0.4	3.7 ± 0.5	22 ± 0.7	6.5 ± 0.1	43 ± 3	84 ± 2	1.9 ± 0.1	4.7 ± 0.3	73
	Organic	25	26 ± 1	1.9 ± 0.1	14 ± 0.3	22 ± 1.2	2.5 ± 0.1	13 ± 0.3	3.7 ± 0.4	4.3 ± 0.5	22 ± 0.8	6.4 ± 0.1	40 ± 3	88 ± 2	1.8 ± 0.1	4.5 ± 0.2	70

Note: Within saturated and non-saturated soils, no statistically significant differences were observed between the soils with mineral and organic fertilization (*n* = number of farms sampled, total number of farms = 90).

**TABLE 4** Pearson correlation coefficients ( $r$ ) for the soil clay content (%), aluminium (Al-ox,  $\text{g kg}^{-1}$ ) and iron (Fe-ox,  $\text{g kg}^{-1}$ ) oxides in all studied soils, and in soils with clay <30% or clay >30%.

	All soils			Clay <30%			Clay >30%				
	Clay	Al-ox	Fe-ox	Clay	Al-ox	Fe-ox	Clay	Al-ox	Fe-ox		
Clay	1			Clay	1		Clay	1			
Al-ox	0.16	1		Al-ox	-0.28	1	Al-ox	<b>0.30</b>	1		
Fe-ox	<b>0.63</b>	<b>0.23</b>	1	Fe-ox	<b>0.69</b>	0.016	1	Fe-ox	0.16	<b>0.31</b>	1

Note: Significant correlations bolded ( $p < 0.05$ ).

explanatory variable for MAOM in clay <30% soils, whereas it was significant in all the other models.

## 4 | DISCUSSION

### 4.1 | OC, MAOC and POC in the soils

Contrary to our expectation, we did not find that the implementation of organic fertilization practices resulted in a higher total OC content of soils, when comparing to mineral fertilization (Table S2). OC in minerally and organically fertilized soils was on average 29.9 and 28.8  $\text{g OC kg}^{-1}$  soil, respectively. This result differs from studies that showed increase in OC at least in the longer term after changing from mineral to organic fertilization (Alvarez, 2021; Just et al., 2023; Maillard & Angers, 2014; Poulton et al., 2018).

There are several potential explanations for the similarity of soil OC contents in our soils that differed in fertilization regime. As plants are important in bringing OC to the soil via root exudates and crop residues (Jackson et al., 2017), it is possible that as long as there is sufficient amount of nutrients to maintain a specific level of primary productivity, the type of fertilization (mineral vs. organic) in some cases is not a decisive factor for the soil OC storage (Gocke et al., 2023; Gregorich et al., 1996; Ladha et al., 2011). However, it is likely that longer-term data on fertilization, including the specific amounts of OC applied with it, would have been needed to ascertain the effects of mineral vs. organic fertilization on the OC in our study. It is also possible that in combination with the aforementioned limitations in our data, we did not detect higher OC stocks in organically fertilized soils due to relatively high baseline levels of OC in the Finnish arable soils (Heikkinen et al., 2013). In this case, the pre-existing OC pool may mask OC additions by organic fertilization as it is difficult to discern small gradual changes in soil OC levels (e.g., Schrumpp et al., 2011). Furthermore, one possibility is that part of the OC from the organic fertilizers is located below the ploughed layer

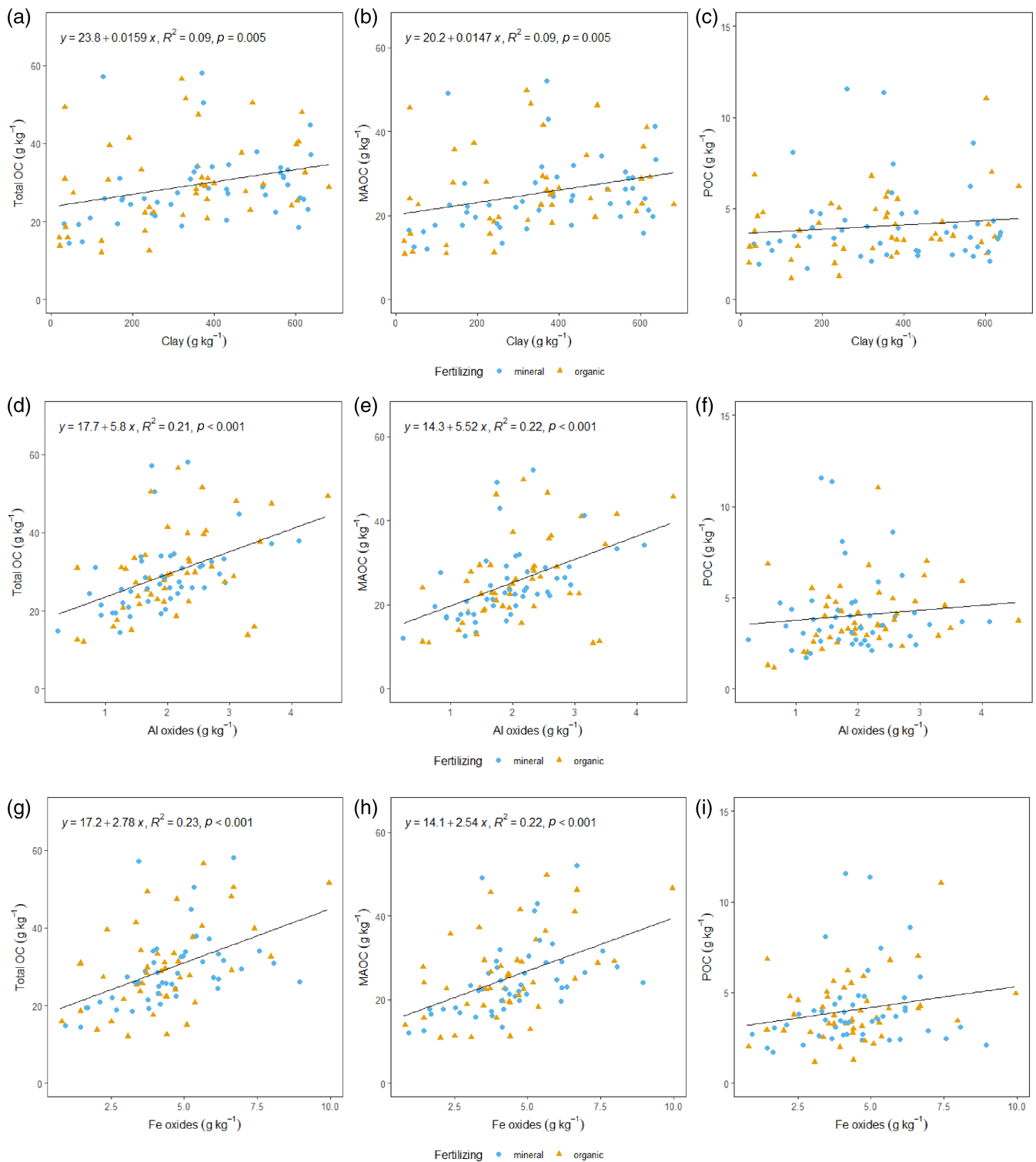
(i.e., below 20 cm soil depth we studied here) as ploughing and leaching may translocate OC from the organic fertilizer into deeper soil layers (e.g., Kätterer et al., 2014; Salonen et al., 2023; Skadell et al., 2023).

Similarly, the type of fertilization had no effect on the OC contents of the MAOM and POM fractions (Table S1). This is in line with what has been previously reported for the Finnish arable topsoil (0–20 cm) in field trials comparing mineral vs organic systems after 35 years (Mayer et al., 2022) and after 24 years (Salonen et al., 2023). This may further indicate that comparable MAOC and POC levels can be achieved with both organic and mineral fertilization, as long as in mineral farming systems, there are enough nutrients to support the plant growth providing OC inputs to the soil.

Across the studied soils, the proportion of OC in MAOC was relatively constant, (83%–89% of the total OC) and this result agrees with what has been determined before for the Finnish arable clay soil (83%–87% of OC in MAOC; Salonen et al., 2023), for temperate arable soils (86%; Begill et al., 2023) and in a global meta-analysis (83%, Matus, 2021), indicating that soils of the agroecosystems across differing environments and climates are having corresponding proportions of the OC in the MAOC and POC fractions.

### 4.2 | Testing OC saturation concepts in the studied soils

There was a strong positive linear relationship between total OC and MAOC across the range of OC contents (12 to 58  $\text{g total OC kg}^{-1}$  soil, Figure S1). A similar relationship was found by Begill et al. (2023). In contrast, some studies have shown that after a specific OC content, the relationship between total OC and MAOC diminishes. For example, Cotrufo et al. (2019) observed this levelling off after a total OC content of 50  $\text{g kg}^{-1}$  in a set of European soils, which was not the case in the current study despite using a similar physical MAOM/POM fractionation method. Our study was restricted to a set of



**FIGURE 3** Simple linear regressions for total OC, MAOC and POC (g kg<sup>-1</sup> soil) with clay, Al and Fe oxides as explanatory variables in fields ( $n = 90$ ) with mineral (blue,  $n = 46$ ) or organic (orange,  $n = 44$ ) fertilization. In case of a significant relationship ( $p < 0.05$ ), a regression line was added to illustrate the relationship.

mineral arable soils from the boreal climate zone with a very specific pedogenic history (i.e., formed by abrasion by ice, Koljonen, 1992). Therefore, our results possibly better reflect soil OC saturation status in the specific case of boreal agricultural soils.

We estimated the feasible maximum amount of MAOC under the prevailing agricultural management for our soils with boundary line analyses and found it to be 55 g MAOC kg<sup>-1</sup> clay+silt (Figure 2, Table 2). This estimate sits between the proposed maxima (Six et al., 2024)

TABLE 5 Best-fit regression models from AIC-driven model selection explaining total OC and MAOC.

	OC fraction <sup>a</sup>	Soils	Regression model	Adj. R <sup>2</sup>
1	Total OC	Clay <30%	0.03 clay + <b>5.06 Al<sub>ox</sub></b> - <b>0.86 pH</b> - <b>0.10 MAP</b> - 4.26 fertilization + 129.9	0.33
2		Clay >30%	-0.02 clay + <b>6.56 Al<sub>ox</sub></b> + <b>1.57 Fe<sub>ox</sub></b> - <b>0.10 MAP</b> + 83.2	0.50
3		All soils	<b>4.91 Al<sub>ox</sub></b> + <b>1.91 Fe<sub>ox</sub></b> - 3.91 pH - <b>0.08 MAP</b> + 89.8	0.44
4		All soils	<b>0.008 clay &amp; silt</b> + <b>5.26 Al<sub>ox</sub></b> + <b>1.26 Fe<sub>ox</sub></b> - 3.78 pH - <b>0.09 MAP</b> + 87.5	0.46
5	MAOM-C	Clay <30%	<b>3.56 Al<sub>ox</sub></b> - <b>0.97 pH</b> - 0.06 MAP - 3.94 fertilization + 116.4	0.36
6		Clay >30%	-0.019 clay + <b>6.34 Al<sub>ox</sub></b> + <b>1.39 Fe<sub>ox</sub></b> - <b>0.09 MAP</b> + 76.4	0.53
7		All soils	<b>4.65 Al<sub>ox</sub></b> + <b>1.69 Fe<sub>ox</sub></b> - <b>4.48 pH</b> - <b>0.08 MAP</b> + 86.8	0.47
8		All soils	<b>0.008 clay&amp; silt</b> + <b>5.01 Al<sub>ox</sub></b> + <b>1.01 Fe<sub>ox</sub></b> - <b>4.34 pH</b> - <b>0.08 MAP</b> + 84.4	0.49

Note: Models were tested for all soils together ( $n = 90$ ) and for soils with a clay content <30% ( $n = 35$ ) and >30% ( $n = 55$ ), separately. Explanatory variables were clay content ( $\text{g kg}^{-1}$ ), clay plus silt content ( $\text{g kg}^{-1}$ ), Al and Fe oxides ( $\text{g kg}^{-1}$ ), cumulative long-term annual precipitation (MAP;  $\text{mm year}^{-1}$ ) and yearly mean temperature (MAT;  $^{\circ}\text{C}$ ; 19-year average), pH and fertilization (mineral or organic, coded 0 and 1, respectively). Significant ( $p < 0.05$ ) explanatory variables bolded. More model details in Table S3.

<sup>a</sup>In the models 1–3 and 5–7, clay as an explanatory variable. In the models 4 and 8, clay + silt as an explanatory variable.

for 1:1 clay-mineral-dominated soils ( $46 \text{ g MAOC kg}^{-1}$  clay+silt) and 2:1 clay-mineral-dominated soils ( $82 \text{ g MAOC kg}^{-1}$  clay+silt). The result of the boundary line analyses is consistent with what could be expected based on background knowledge of the mineralogy of Finnish soils since they are formed by ice abrasion and are relatively young (Koljonen, 1992) and non-weathered (Keskinen et al., 2022) and thus are assumed to have lower surface activity than 2:1 clay mineral dominated soils. According to the boundary line analyses, studied soils had 45%–118% of the estimated feasible MAOC ( $\text{g OC kg}^{-1}$  clay+silt) under the current arable land management, and only the lowest clay content interval ( $0\text{--}100 \text{ g kg}^{-1}$ ) was above the estimated maximum (118% of the estimated feasible MAOC). However, it is worth emphasizing that we do not know whether the soils selected in this study and for the boundary line analyses are truly representative of a maximum achievable OC content with the current agricultural management as we do not have time series measurements of the soils that confirm a steady state of OC in terms of a specific level of OC inputs. Nonetheless, since our dataset is relatively large and contains a diverse selection of farms from the southern half of Finland with different farming histories, we can assume that the results reveal a reasonable estimate of the maximum MAOC of  $<60 \mu\text{m}$  particle size fraction under the current agricultural management.

We also assessed soil carbon saturation with Hassink's equation (Hassink, 1997; Table 2) with two particle size cut-offs for clay+silt:  $<20 \mu\text{m}$  (as in Hassink, 1997) and  $<60 \mu\text{m}$  (as theoretically, minerals up to this size have relevant specific surface area for MAOC binding; Six et al., 2024). With this approach, all soils with the clay content  $>200 \text{ g kg}^{-1}$  (72% of the studied soils) had OC saturation deficit while soils with the lowest studied clay

content ( $0\text{--}100 \text{ g kg}^{-1}$ ) were found to be above their theoretical maximum (i.e.,  $>100\%$ ) MAOC saturation.

As some of the soils, with a clay content  $<100 \text{ g kg}^{-1}$ , were found to be oversaturated with MAOC (i.e., having more than 100% of the maximum MAOC proposed by the Hassink's equation), it is possible that the used approaches are not well suited for the soils in question. These saturation estimation approaches oversimplify the binding capacity associated with MAOC as they only take into account soil texture, whereas there is a multitude of other factors (such as climate, vegetation, soil chemistry, Al and Fe oxides) affecting soil OC stabilization soils (e.g., Guillaume et al., 2022; Rasmussen et al., 2018; Six et al., 2002; Soenne et al., 2024).

Furthermore, observed oversaturation could also indicate methodological error in the size fractionation of MAOM ( $<53 \mu\text{m}$  soil) / POM ( $>53 \mu\text{m}$  soil). Similarities of the C to N ratios of MAOM and POM in the low clay soils ( $<100 \text{ g clay kg}^{-1}$  soil, C to N ratio = 18, Table 1) may imply POM contamination, for example, fine-sized POM passing through the sieve to the MAOM fraction during the MAOM/POM fractionation, which would increase the OC content of the MAOM. Due to the relatively high clay content of most of our soils, we needed to use glass beads to assist full dispersion of the soils, and the glass bead approach may have led to some crumbling of the larger POM fragments into smaller, MAOM-sized fragments ( $<53 \mu\text{m}$ ).

Yet, it is possible that the observed similarity of the C to N ratios of the MAOM and POM in the  $<100 \text{ g clay kg}^{-1}$  soil is not a sign of contamination but instead indicates a chemical resemblance of MAOC and POC in the low clay soils. Some studies have found MAOM and POM to be chemically resembling (e.g., Chang et al., 2024; Yu et al., 2022), and Yu et al. (2022) reported C to N ratios

corresponding to the ones in here in MAOM and POM fractionated with the same method (size cut-off 53  $\mu\text{m}$ ). Also, it has been shown that in coarse soils, POM-sized MAOM (i.e., mineral-bound MAOC >53  $\mu\text{m}$ ) can have higher C to N ratio than smaller-sized MAOM (<53  $\mu\text{m}$ ; Samson et al., 2020, Sokol et al., 2022). Hence, we cannot rule out the possibility that the resembling C to N ratios of the MAOM and POM in the studied low clay soils are a true finding.

### 4.3 | Soil properties, climate parameters and OC, MAOC and POC

As expected, we found that Al and Fe oxides were more strongly correlated with OC and MAOC than clay (Figure 3). However, as simple linear regressions could explain only 9%–23% of the variation in OC and its fractions, neither clay, Al and Fe were well suited as single predictors to explain OC and its fractions in the studied soils. As soil OC and clay content have previously been reported to be connected (e.g., Arrouays et al., 2006; Kaiser & Guggenberger, 2003; Wiesmeier et al., 2019), it was somewhat surprising that the soil clay content was not associated strongly with OC (clay explained only 9% of OC and MAOC variation; Figure 3). Some previous studies have also stated that clay content is not the only or even an important determinant of OC (Prout et al., 2021; Rasmussen et al., 2018; Salonen et al., 2023). One possible explanation for this in the current study relates to the relatively low primary productivity of soils with a high clay content. As very clayey soils in Finland tend to have lower yield levels than coarser soils, there is possibly a lower plant-derived OC input in the soil (Soenne et al., 2021) which could lead to lower SOM levels compared to soils with a higher primary productivity.

While Al and Fe oxides had a stronger correlation with OC and MAOC than the soil clay content, also they both remained poor single predictors for the amount of soil carbon. Other studies from similar soils have found larger correlations between Al oxides and OC. Rasmussen et al. (2018) found Al and Fe oxides to be most important predictors of OC in humid climates. In our data, Al oxides explained 21% of the variation in OC (clay content 2%–68%), whereas in a Swedish field experiment, they explained 48% in soils with a clay content of 17%–42% (Fukumasu et al., 2021). However, our soils estimated to be MAOC-saturated had relatively more Al and Fe oxides per gram of clay or clay+silt than non-saturated-soils (Table 3), indicating a close relationship between oxides and MAOC (Hall & Thompson, 2022; Rasmussen et al., 2018). In the multiple regression models (Table 5), Al oxides were particularly important as an explanatory

variable in all the models, whereas Fe oxides were significant for OC and MAOC only in soils with high clay content (>30%). Soil pH correlated negatively with OC and MAOC in soils with low clay (<30%). This is consistent with previous research, as low soil pH has been found to correlate with slower OC decomposition (Keiluweit et al., 2016; Slessarev et al., 2016) and OC accumulation (Lugato et al., 2021). On the other hand, low pH could lead to lower primary productivity and lower OC input via roots (Young et al., 2021), possibly lowering soil OC.

Consistent with the simple linear regressions, clay content was not a significant predictor in any of the multiple regression models. However, clay+silt was a significant predictor of OC and MAOC when all the studied soils were included in the analysis. It is possible that this is a consequence of higher primary productivity and plant-derived OC inputs in coarser soils (Soenne et al., 2021), as lower porosity of the more clayey soils may limit plant OC inputs.

In a global meta-analysis, Jobbágy and Jackson (2000) reported that soil total OC content increased with precipitation and decreased with temperature. Likewise, Hansen et al. (2024) found that MAP was connected to higher MAOC levels on a global scale. Opposite to these findings and our expectations, OC decreased with increasing precipitation, and clay and temperature had no relationship with OC or MAOC in our multiple regression analyses. It is possible that the range of mean temperature in our data (3.3–6.4°C) is not wide enough to make a noticeable difference in the soil OC content as for the large part of year, the studied soils are far from the optimal temperature for the microbial growth (20–25°C for Boreal agricultural soil; Pietikäinen et al., 2005) which halts OC decomposition and transformation processes.

Our finding that the mean annual precipitation (range 548–725 mm year<sup>-1</sup>) was negatively correlated with OC and MAOC was unexpected as greater MAP has been previously connected to larger OC as prevalent moist conditions can cause anoxic conditions which hinder SOM decomposition (Jobbágy & Jackson, 2000; Wiesmeier et al., 2019). On the other hand, prevalent rain may restrain OC inputs into the soil as it may limit plant growth and consequently curb OC inputs to the soil due to waterlogging and following anoxic conditions (Drew, 1997). As another example, temperature affects yields, and higher temperature could lead to higher OC inputs to the soils via roots. In addition, temperature affects microbial activity and higher temperature could lead to a faster decomposition of SOM. These examples illustrate that many of the factors affecting OC are interconnected. Therefore, reliably disentangling effects that they individually have on OC is challenging. In addition,

climate-related gradients can be further confounding assessing the effects of the individual factors.

All in all, the best-fit models explained 33%–50% of the variation in total OC and 36%–53% of the variation in MAOC. The relatively low model fit could indicate that other factors explaining soil OC that were not included in this study (such as plant productivity, topography, long-term land use and fertilizing history) could affect OC/MAOC levels in our soils. In particular, data on soil productivity/ yield levels could improve the models as most of our soils were found to have low carbon saturation, with the implication that mineral adsorption surfaces were not a limiting factor.

## 5 | CONCLUSIONS

We fractionated soil from 93 arable fields with a physical MAOM (<53  $\mu\text{m}$ ) / POM (>53  $\mu\text{m}$ ) fractionation method. The total amount of OC (12–58  $\text{g kg}^{-1}$  soil) was not affected by the type of fertilization (mineral vs organic) and the share of OC in MAOC (86  $\pm$  3%) was found to be relatively stable and also not affected by fertilizer type. The largest total OC and MAOC contents were measured in high clay soils, but considering the general assumption of the significant role of clay in defining the protective capacity for MAOC, we observed surprisingly high MAOC contents even in the low clay soils. The applied soil OC saturation assessment with Hassink's equation revealed that the lowest clay content soils were above their predicted maximum (i.e., >100%) MAOC saturation, and as expected, soils with higher clay content have further OC accrual potential. Similarly, based on the boundary analysis, the low clay soils had the highest carbon saturation. As the low clay soils seemed to be oversaturated with OC/MAOC, it is possible that the applied OC saturation estimation approaches misjudge the OC accrual capacity of these soils because they rely merely on soil textural information. Also, as clay was not an important predictor for soil OC in the multiple regression models, there are indications that in the studied, relatively moderately weathered soils, clay content is not a decisive factor for the amount of stabilized OC. In our soils, single soil properties (clay, Al and Fe oxides) were not well-suited as predictors for total OC or MAOC, but multiple regression models revealed that soil parameters (in particular Al and Fe oxides and pH) and mean annual precipitation combined could explain more of the variation in soil carbon. Multiple regression models at their best explained 53% of the variation of MAOC, indicating that there are other context-dependent factors (such as long-term land use history) contributing to soil OC-related processes that deserve attention in further studies.

## AUTHOR CONTRIBUTIONS

**Anna-Reetta Salonen:** Conceptualization; investigation; writing – original draft; formal analysis; data curation.

**Ron de Goede:** Conceptualization; writing – original draft; writing – review and editing; formal analysis.

**Rachel Creamer:** Conceptualization; writing – review and editing. **Jussi Heinonsalo:** Conceptualization; writing – original draft; writing – review and editing; funding acquisition. **Helena Soinne:** Conceptualization; writing – original draft; writing – review and editing.

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## CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare.

## DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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