Soil Use and Management

WILEY | BRITISH SOCIETY OF SOIL SCIENCE

ORIGINAL ARTICLE OPEN ACCESS

The Dependence of Cereal Yields on Soil Organic Carbon in Concert With Other Soil Properties and Management

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Received: 22 April 2025 | **Revised:** 22 April 2025 | **Accepted:** 27 May 2025

Funding: This work was supported by Ministry of Agriculture and Forestry of Finland, 2217/03.01.02/2015. Academy of Finland, 352435.

Keywords: agricultural productivity | fertilisation | nitrogen | soil fertility | statistical modelling | texture

ABSTRACT

Maintaining or even enhancing the productivity of arable soils is essential for ensuring food security, in addition to meeting feed and fibre needs. Relationships between yield, soil properties and management are complex and vary between environments; therefore, site-specific knowledge of yield-governing factors is needed to close any potential yield gaps. Soil organic carbon content (SOC) is a potential key factor in soil fertility management due to its manifold influence on soil functions. This study assessed the association of spring cereal yield with SOC and other soil properties as well as management practices in boreal mineral soils. Linear mixed-effects models were applied on a data set collected from 43 field sites in Finland varying in production potential with special interest in yield response to soil C content. Soil data comprised soil texture and total C content, plant-available nutrient concentrations, pH and cation exchange capacity. Management data consisted of information on the use of fertilisers and liming, crop rotation, method of tillage, plant protection measures and water regime. Many of the soil properties were intercorrelated, and the most appropriate model variables were selected after tentative examinations. The resulting model showed a significant positive yield response of $342 \pm 100\,\mathrm{kg\,ha^{-1}}$ per 1 percentage point increase in SOC. Soil clay content had a negative effect on yield, with a decrease of $33.9 \pm 15.7\,\mathrm{kg\,ha^{-1}}$ per percentage point increment when the proportion of clay exceeded 40%. In addition, nitrogen (N) fertiliser rate, which showed a positive connection with other management efforts, significantly affected cereal yields ($56.6 \pm 9.7\,\mathrm{kg\,ha^{-1}}$ yield increase per kilogram of N applied) for spring varieties of barley, oats and wheat. Liming and use of fungicides also had a clear positive effect on yields. The results indicate that even in boreal mineral soils with a relatively large range of SOC content (range 1.3%–9.1% in present study), high SOC has a positive effect on yield. Furthermore, SOC is especially beneficial in soils with > 40% clay content where it can alleviate the negative yield effects of high clay content. The results underline that sustaining SOC reserves in the northern soils is vital for maintaining soil productivity apart from its importance for mitigating climate change.

1 | Introduction

Although the intensification of agriculture over the last decades has led to a desirable increase in global food production, it has simultaneously endangered both the quality of the environment and the soils, that is, the capacity of soils to function optimally and support crop productivity (Cassman 1999; Giller et al. 1997; Houlbrooke et al. 2011; Matson et al. 1997; Stoate et al. 2001). Moreover, challenges in feeding the growing human population and increased demand for plants for non-food uses continue to exert pressure on agricultural production. Maintaining, or preferably enhancing, the productivity of existing arable land is also essential to restrict further clearing of diminishing natural habitats for cultivation (Foley et al. 2011). However, for vast areas of cultivated land, crop yields are in decline or previous positive trends in yields have stagnated (Ray et al. 2012). Sustainable management methods for closing the gap between realised and potentially achievable productivity are therefore urgently needed (Foley et al. 2011; Garibaldi et al. 2017; Godfray et al. 2010; Herrero et al. 2010).

Yield levels are governed by numerous biophysical and socioeconomic factors, including the availability of resources, capital and expertise, as well as the burden on the environment and the choices of management practices (Ray et al. 2012). Among all these factors, soil quality is indisputably a fundamental component in determining agricultural productivity. The quantity and availability of nutrient reserves, the extent of water-holding capacity and the structure of the matrix for root growth all influence crop growth. Soil quality is often evaluated through measurable biological, chemical and physical key indicators that are selected based on the type of ecosystem and the overall objectives of the assessment scheme (e.g., Andrews et al. 2002; Arshad and Martin 2002; Askari and Holden 2015; Obade and Lal 2016). The most frequently used variables include pH, organic matter or carbon contents, total or plant-available nutrients and harmful metals, cation exchange capacity (CEC), electrical conductivity (EC), soil depth, texture, bulk density, porosity, aggregation, structural stability, penetration resistance, water storage and infiltration properties, earthworm density, microbial biomass, soil respiration and nitrogen mineralization (Bünemann et al. 2018).

Previous studies have shown the relationships between yield and soil variables to be far from straightforward, as the dependencies and interactions of yield-forming factors vary among soil types, environmental conditions and crop species (e.g., Frogbrook et al. 2002; Kaspar et al. 2004; Mallarino et al. 1999). Intercorrelations between soil properties further complicate data analyses and the interpretation of results (Arshad and Martin 2002; Mallarino et al. 1999). Although consistent relationships have been firmly established between yield and, for example, soil nutrient status, CEC, pH, elevation, slope, texture and water-holding capacity (Anthony et al. 2012; Ping et al. 2004; Shatar and McBratney 1999; Stein et al. 1997), a significant proportion of the variation in yields may remain unexplained, or the relationships between yield and the measured soil characteristics may, overall, be weak (Bourennane et al. 2004; Stein et al. 1997).

Among the soil properties potentially affecting crop yields, organic matter content stands out, as it has an extensive influence on several soil functions such as nutrient cycling, water storage and habitat provision (Baveye et al. 2020; Lal 2020; Obalum et al. 2017) while simultaneously playing a role in climate regulation (Crowther et al. 2016; Lal et al. 2021). The inherent properties of soil, as well as the climatic factors, influence soil's capacity to store organic matter (Richardson et al. 2023). The main mechanisms of organic matter accumulation in different soil types include sorption onto mineral surfaces, aggregate formation that provides physical protection and translocation followed by burial in the subsoil (Kögel-Knabner and Amelung 2021). Therefore, soil texture plays a central role in SOC-related processes, as it affects both aggregate formation and the availability of reactive mineral surfaces for organic matter stabilisation. In general, the mineral agricultural soils in Finland are losing organic matter (Heikkinen et al. 2013). However, their C content has remained higher than in southern parts of Europe (Matschullat et al. 2018). In addition to Finland's cooler climate, with below-zero temperatures during winter, this relatively high C content can be attributed to the shorter time since forest clearance for agriculture (Heikkinen et al. 2013), which underscores the importance of historical soil management in shaping SOC levels (Heikkinen et al. 2022).

Considering the key role of organic matter in soil functioning, decreasing trends in soil organic matter content are of concern regarding both food security and environmental conservation (e.g., Barros and Fearnside 2019; Bellamy et al. 2005; Bond-Lamberty et al. 2018; Heikkinen et al. 2022). However, both positive (Oldfield et al. 2019, 2022), negative (Schjønning et al. 2018), and insignificant (Hijbeek et al. 2017) relationships between soil organic matter and crop yields have been reported, reflecting the complexity of yield formation and suggesting the presence of regionally specific main drivers.

Furthermore, many key functional soil properties that dictate potential yields are sensitive to management. Fertilisation strategy (Edmeades 2003), manure applications (Gerke 2022) and other organic amendments (Larney and Angers 2012), tillage method (Rasmussen 1999), handling of crop residues (Blanco-Canqui and Lal 2009) and crop rotation (Karlen et al. 2006) are known to affect soil productivity. Understanding the site-specific effects of management on crop yields would enable case-specific selection of the most sustainable and profitable management options.

The objective of this study was to investigate the association between yield levels of spring cereal crops and soil organic matter content in mineral agricultural soils in Finland while also accounting for other selected soil properties and management practices. The inference was based on a linear mixed model that accounted for fixed effects as well as the correlation structure of the data. The aim is to advance knowledge on soil properties essential for maintaining the productivity of northern soils, whose significance in global food production may increase due to climate change (e.g., Wheeler and Von Braun 2013).

2 | Material and Methods

2.1 | General Description of the Area and Agriculture in Finland

Finland lies within the boreal zone which experiences cold winters and relatively warm summers. The duration of the growing season ranges from 101 days in northern Finland to 195 days in southern Finland (Kersalo and Pirinen 2009). The study regions of the present study are located in the hemiboreal and southern boreal zones. Mean annual precipitation (609 mm) ranges from 441 to 811 mm, with the highest values occurring in southern Finland.

The formation of soils in Finland has been influenced by the Weichsel glacial period which ended about 11,500 years ago. Due to their young pedogenetic age, most soils are relatively weakly developed and contain quartz, plagioclase and K-feldspar as the dominant mineral components (Keskinen et al. 2022). The majority of soils in Finland have a cryic temperature regime, characterised by low soil temperatures (Yli-Halla and Mokma 1998). Cultivated clay soils in Finland are typically classified by the IUSS Working Group WRB (2007) as (Vertic Luvic) Stagnosols or (Luvic) Gleysols in wet depressions, whereas silt soils are classified as (Stagnic) Regosols and fine sand soils with deeper clay-rich layers as (Endogleyic Luvic) Planosols. Very fine sand or fine-sandy moraine soils are commonly classified as (Endogleyic) Cambisols, whereas podzolized coarse mineral soils are classified as (Gleyic) Podzols (Yli-Halla and Nyborg 2013). In general, the plough layer of agricultural soils in southern Finland is characterised by a clayey texture (clay content > 30%), whereas medium-textured mineral soils are common in central and western, eastern and northern parts of the country. Additionally, the western and northern parts are also characterised by organic soils (Heikkinen et al. 2013; Lemola et al. 2018). The majority of fields are artificially drained due to occasionally excessive moisture (Puustinen et al. 1994), and drainage enables field traffic in early spring and late autumn.

In Finland, agricultural land accounts for 7.5% of the total land area, with cereal and grass production (including grass fallow areas) covering 46% and 45%, respectively (OSF 2018a). Among the provinces included in the study, grass production occupies 67% of the utilised agricultural area in central-eastern Finland, whereas cereals are the dominant crops (53%–71%) in southern and southwestern Finland, with barley (*Hordeum vulgare* L.), oats (*Avena sativa* L.), and wheat (*Triticum aestivum* L.) being the main cereals (OSF 2018b). Dairy and beef production systems are characteristic of central-eastern Finland, whereas pig and poultry farming are typical in southern and southwestern Finland. Production of other crops, such as sugar beet (*Beta vulgaris* L.), turnip rape (*Brassica rapa* subsp. *oleifera* L.), oilseed rape (*Brassica napus* subsp. *oleifera* L.), pea (*Pisum sativum* L.) as well as horticultural activities are also concentrated in southern Finland (OSF 2017).

2.2 | Sampling Sites, and Soil and Plant Analyses

The study included a total of 43 sampling sites located in central-eastern Finland and in the southern coastal and southern inland regions of southwestern Finland (Figure 1, Table S1: Data S2). The sampling locations were situated within four cultivation zones,

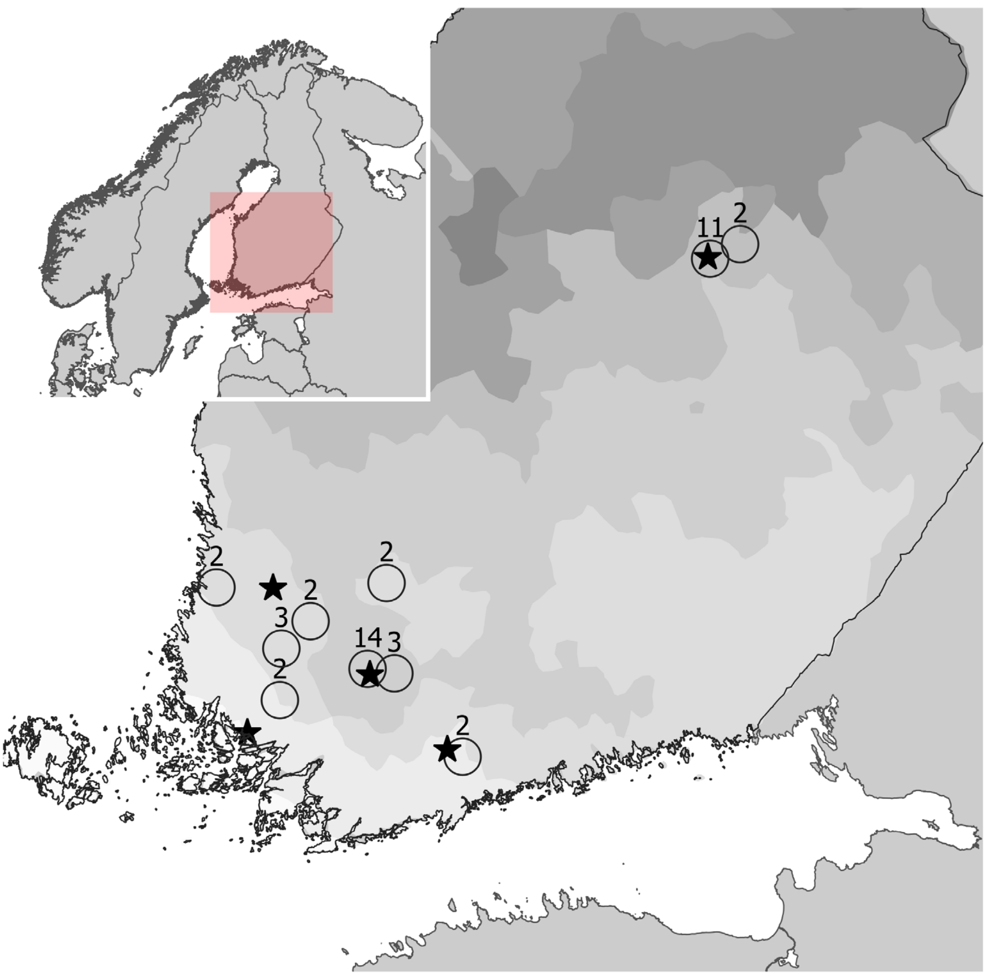

FIGURE 1 | Locations of the sampled fields ($n = 43$) in southwestern and central-eastern Finland (circles), and the weather stations of the Finnish Meteorological Institute (stars). Different cultivation zones are shown in varying shades of grey. The zoning is based on the length of the growing season, the sum of the effective temperature and winter conditions.

defined based on the length of the growing season, accumulated effective temperature and winter conditions. The mean growing season length (calculated for the period 1991–2020) ranged from 185 days in the south to 155 days in the north, whereas mean precipitation during the growing season varied from 380 mm in the south to 320 mm in the north (FMI). Weather data for the study years and for each cultivation zone were collected from weather stations of the Finnish Meteorological Institute and is provided in Data S1 and S2. Locations of the weather stations are presented in Figure 1.

In 2016, field parcels from experimental stations managed by the Natural Resources Institute Finland (Luke) in Jokioinen (southern inland) and Maaninka (central-eastern) were examined. The plots were selected from mineral soil fields (< 10% SOC) designated for sowing cereal crops. Fields of both high and low productivity were included based on yield records from previous years and the practical experience of station managers and field staff.

In 2017, the field parcels from experimental stations were supplemented with parcels under cereal cultivation from private farms in the same geographical regions (Figure 1) to ensure inclusion of existing variability in soil type and management of crop and soil. Farmers were asked to either select distinct plots they considered to be of high or low productivity or to identify specific sites with differing productivity within a single plot. The productivity classification was largely subjective, as no explicit yield level thresholds were established, but it was designed to ensure inclusion of sites with varying growth potential. Soils with higher than 10% SOC content were excluded.

Background information on the selected fields was collected from managers of the experimental farms of the Natural Resources Institute Finland (Luke) at Jokioinen and Maaninka, as well as from private farmers. They provided approximate average long-term yield levels of spring cereals for the sites, along with information on the use of fungicides, growth regulators, lime, organic fertilisers, crop rotation, tillage methods and water-related risk levels. In addition to the sampling years 2016 and 2017 included in this study, respondents were asked to consider the preceding 5 years before sampling and report the applied NPK rates during the sampling year(s) (Table S1: Data S2).

At each sampling site, a representative central sampling point was first identified. Subsequently, three surrounding sampling points were positioned on a circle approximately 5 m away from the central point. Yield and soil profile samples were collected at all four sub-sampling points. Additionally, a soil fertility sample was taken from each central sampling point.

Yield samples were collected after ripening by harvesting the entire plant stand within a 75 × 75 cm frame. In Finland, the common distance between cereal plant rows is 12.5 cm; thus, the sample consisted of six plant rows. The harvested plant material was separated into spikes and straw, dried at 60°C and weighed. All spike samples collected from Jokioinen in 2016, as well as one sample per field from Jokioinen and Maaninka in 2017, were separated into grains and chaff (e.g., awns) using a threshing machine. Grains were processed through the thresher 4–5 times until the number of visible impurities was comparable to the quality produced by combine harvesters. When only one spike sample from the field was threshed, it was used to calculate the proportion of grains in the other spike samples from that field. For the 11 fields where threshing was not conducted, all 168 available threshed samples were used to estimate the relationship between spike yields and grain yields (44 grain samples; for details of the calculation see Data S3). On selected fields, the grain yield obtained by the 75 cm × 75 cm quadrat frame method and calculated according to the threshing result was compared to the grain yield acquired by a trial plot harvester covering a much larger area.

Soil profile samples were taken from the plant row using an auger with a diameter of approximately 4.5 cm to a depth of 40 cm. In 2016, the profile samples were collected after harvest, whereas in 2017, they were collected during June–July, during vigorous plant growth. From the acquired soil cores, total C and N, the number of roots per cm^2 of soil and soil bulk density were determined from the topsoil (0–20 cm) and subsoil (20–40 cm) layers. In brief, the soil cores were split into two pieces, and roots appearing on the freshly broken faces were counted. The mean number of roots per broken face was then divided by the cross-sectional area of the soil core to calculate root density. The core samples were subsequently dried at 40°C and weighed to determine bulk density, after which they were ground to pass through a 2-mm sieve and analysed for C and N via dry combustion (Dumas method, Leco TruMac CN). In these acidic soils, which are very low in carbonates, the total C content was assumed to be practically equal to the amount of SOC.

Soil fertility samples were collected after harvest from the 75 × 75 cm harvested area at the central sampling point by combining three replicate samples taken from both 0 to 20 cm and 20–40 cm depths using an auger (Ø 2.7 cm). The samples were dried at temperatures below 40°C, ground to pass a 2-mm sieve and analysed for texture, pH, EC, CEC and soil test P, Ca, K and Mg concentrations using acid ammonium acetate (aAAc) extraction.

The particle size distribution of the soils was determined by the pipette method of Elonen (1971) at Eurofins Viljavuuspalvelu Oy, Mikkeli. All other analyses were conducted at the Luke laboratories in Jokioinen. Soil pH and EC were measured from a soil-water suspension (1:2.5, *V/V*). Neutral ammonium acetate (AAc, 1 M CH_3COONH_4, pH 7.0) extraction with a soil-to-solution ratio of 1:5 (*W/V*) was used for CEC analysis as described in Räty et al. (2021). For determining an index of plant available nutrients, the aAAc extraction (0.5 M CH_3COONH_4, pH 4.65) was performed with a soil-to-solution ratio of 1:10 (*V/V*) and a shaking time of 1 h (Vuorinen and Mäkitie 1955). The P concentrations (soil test P) of the extracts were analysed by flow injection analysis (Skalar San++ System) while the concentrations of Ca, K and Mg were determined using inductively coupled plasma optical emission spectrometry (ICP-OES; Perkin Elmer Optima 8300).

2.3 | Soil Properties and Management

The mineral soils in the present study represent arable land in southern coastal, southern inland, and central-eastern Finland. Soil pH, SOC content and easily available macronutrient cations (Ca, Mg, K) and P (Table 1, Table S1: Data S2) were within

TABLE 1 | Descriptive statistics of the continuous variables analysed from the soil surface layer (0–20 cm), except for bulk density and the number of roots, which are reported at 20–40 cm depth $n = 43$.

Variable	Unit	Minimum	Median	Maximum
Texture				
Clay (< 0.002 mm)	%	0	38	78
Silt (0.002–0.02 mm)	%	8	18	51
Sand (0.02–0.2 mm)	%	6	21	81
Coarse sand (0.2–2 mm)	%	1	5	40
Bulk density	$g\,cm^{-3}$	1.0	1.4	1.8
SOC	%	1.3	3.1	9.1
C to N-ratio		10.7	13.6	16.3
Clay to C-ratio		0	11.5	22.5
pH		5.1	6.2	7.0
Cation exchange capacity	cmol(+) kg^{-1}	1.7	14.9	34.0
Exchangeable Ca	cmol(+) kg^{-1}	1.2	12.1	22.8
Exchangeable Mg	cmol(+) kg^{-1}	0.3	2.3	12.0
Exchangeable K	cmol(+) kg^{-1}	0.1	0.4	1.5
Soil test P	$mg\,l^{-1}$	0.7	5.7	27.3
Number of roots	cm^{-2}	0.03	0.35	1.19

the range reported in the national monitoring of arable soils (Heikkinen et al. 2013; Keskinen et al. 2016). The present median values of soil test cations were somewhat higher than the national averages, whereas soil test P values were lower, particularly in clay soils (Keskinen et al. 2016; Lemola et al. 2018). The soil test cations (aAAc, pH 4.65) strongly correlate with the exchangeable cations (AAc, pH 7.0) since approximately 80% of the exchangeable cations are extracted using the soil test procedure (Vuorinen and Mäkitie 1955). Consequently, the values of exchangeable cations were used in this study (for results using both methods, see the Table S1: Data S2).

For water regimes (hydrological quality), the fields were classified as either 'poor' or 'satisfactory' (Table 2). Lime use was grouped into three categories: 'used less than 10 years ago', '10–20 years ago', or 'more than 20 years ago'. Crop rotation was categorised as either cereal monoculture, with cereals grown at least 7 years out of ten, or diversified systems, with cereals grown for fewer than 7 years out of ten. Soil tillage management was classified as ploughing or other methods. The use of organic fertilisers, plant disease prevention, and growth regulators were classified as 'yes' or 'no'. The effect of these variables on yield was tested using *t*-test for binary classifications and a mixed model for three categories as in the case of liming using SAS EG 7.1 procedures.

Crop management and cultivation practices for the field parcels are described in Table 2. Autumn ploughing to a depth of approximately 20 cm was the predominant primary tillage practice in central-eastern Finland. Cereal straw residues were primarily incorporated into the soil through ploughing; however, straw residues were also baled and removed from fields when there was demand for their use as bedding material for livestock. In the southern coastal and southern inland regions, conservation tillage practices such as reduced tillage and direct drilling were more common. Dairy slurry was widely used in the central-eastern region, with all research station fields and half of farmers' fields having a history of annual or near-annual slurry application.

2.4 | Prediction Model for Grain Yield

The factors contributing to annual crop yield were investigated using a linear mixed-effects model, with the primary focus on the role of SOC.

The relationships among silt, clay, SOC contents, N fertilisation, and yield were initially explored graphically. Several potential models with different change points for clay ranging from 30% to 45% were tested based on observations from the graphical analyses, in addition to a model with a quadratic term for clay. In addition, we tested all possible models with one interaction term. The best model was selected using the Akaike Information Criterion (AIC) after fitting with maximum likelihood estimation, and the final model was fitted with restricted maximum likelihood estimation (REML).

In the selected model the annual crop yield for field i was expressed as

$$\begin{aligned} \text{Crop yield}_i = \; & \beta_0 + \beta_1 \text{Barley} + \beta_2 \text{Wheat} + \beta_3 \text{Fertilizer} \\ & + \beta_4 \text{Clay}_{40} + \beta_5 \text{Crop rotation} + \beta_6 \text{Total organic C} \\ & + u_i + \epsilon_i, \end{aligned} \quad (1)$$

TABLE 2 | Variables describing crop management and cultivation conditions ($n = 43$).

Categorical variables	Classes and number of observations in them
Cultivation zone	Southern coastal = 9, southern inland = 21, central-eastern Finland = 13
Harvest year	2016 = 16, 2017 = 42
Crop rotation	Cereals at least 7 years out of ten = 27, cereals fewer than 7 years out of ten = 16
Use of organic fertilisers	No = 23, yes = 20
Common autumn soil management	Ploughing = 22, other = 21
Plant disease prevention	No = 21, yes = 22
Plant growth regulators	No = 36, yes = 7
Liming	Less than 10 years ago = 22, 10–20 years ago = 12, more than 20 years ago = 9
Water regime	Poor = 5, sufficient = 38
Continuous variables	**Median (min, max)**
Yield history, DM kg/ha	4000 (1000, 6400)
N rate, kg/ha	99 (54, 180)
P rate, kg/ha	11 (0, 73)
K rate, kg/ha	35 (0, 168)
N in organic fertiliser, kg/ha	0 (0, 102)
P in organic fertiliser, kg/ha	0 (0, 30)

where Barley and Wheat are dummy variables differentiating yield levels of barley and wheat with respect to oats, Fertiliser represents the amount of fertiliser applied (kg inorganic N/ha), $Clay_{40}$ is the percentage of clay exceeding 40% (i.e., 0 for Clay < 40%, and Clay percentage—40% otherwise), Crop rotation is an indicator variable with a value of 0 for crop rotations with cereals grown at least 7 years out of 10, and 1 for rotations with cereals grown for fewer than 7 years out of 10, Total organic C represents the percentage of carbon in the soil. The β-terms denote the regression coefficients for the fixed effects with β_0 being the intercept term, u_i is a block-specific normally distributed random effect with mean zero for the intercept, and ϵ_i is a normally distributed error term. The blocks consisted of 1–2 observations: two observations were grouped into a block if they were either (1) collected from the same plot in 2016 and 2017 or (2) collected from adjacent fields observed in the same year. As a sensitivity analysis, an alternative version of the model was developed, including yield history as a fixed effect. The correlations between continuous variables were relatively weak, with the strongest correlation being −0.43 which was found between $Clay_{40}$ and Total organic C. Thus, no variables were removed due to strong intercorrelations. The normality of the residuals was checked using a Shapiro–Wilk test, and no evidence of model assumption violations was found.

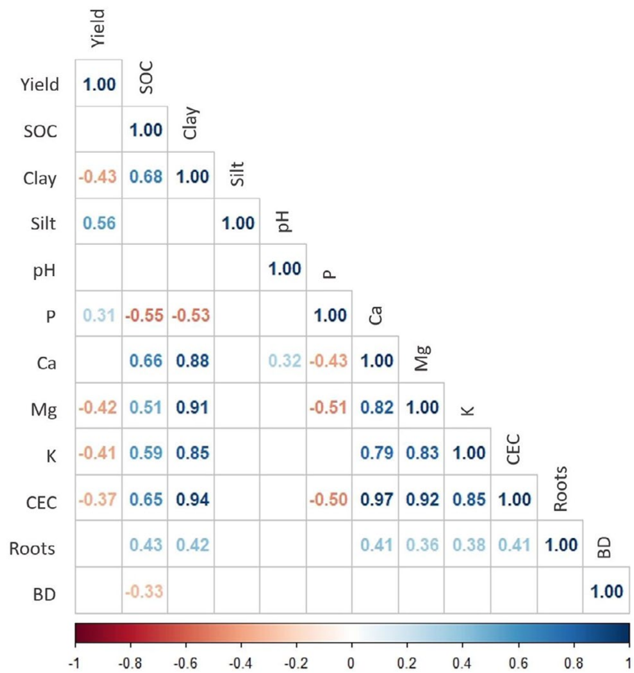

FIGURE 2 | Correlations between soil properties and yield: Spearman correlation coefficients ($p < 0.05$) for continuous variables in 2017.

The model fitting and relevant inferences were performed using the R-package *nlme* (Pinheiro et al. 2022). All statistical analyses were conducted using the statistical software R (R Core Team 2022).

3 | Results

3.1 | Grain Yields

Grain yields harvested from the studied field plots in 2016 and 2017 ranged from 1197 to 9564 kg per hectare, with median yields of 4566 kg ha^{-1} in 2016 and 4911 kg ha^{-1} in 2017 (Data S2). In 2016, barley was the most prevalent crop ($n = 10$), followed by wheat ($n = 5$) and oats ($n = 1$). In 2017, the three cereals were more evenly represented: barley ($n = 15$), oats ($n = 14$), and wheat ($n = 13$).

The grain yield obtained using the 75 cm × 75 cm quadrat frame method, calculated based on the threshing results, was compared to the yield acquired by a trial plot harvester (Data S3, Figure S1). The relationship between these two sampling techniques was strong ($R^2 = 0.86$; $n = 24$), supporting the validity of the 75 cm × 75 cm quadrat frame method for estimating the crop yields.

3.2 | Relationships Between Soil Properties, Fertilisation, and Grain Yield

Statistically significant correlations were observed between yield and clay and silt contents, as well as exchangeable Mg, K, and CEC (Figure 2). Due to the collinearity between clay and exchangeable K, Ca, Mg, and CEC, clay was selected as the explanatory variable for the model.

At low clay contents, yields appeared to increase with increasing clay; however, the relationship became negative at higher clay contents, with the lowest yields recorded from fields with the highest clay content (Figure 3a). Similarly, at low silt contents, yields increased with rising silt levels, but this trend plateaued at silt contents exceeding 20% (Figure 3b). The relationship between silt and yield is closely linked to soil clay content. When clay content is below approximately 30%–40%, a positive correlation with silt levels and yield can be observed. However, at clay contents exceeding 30%–40%, the relationship between silt and clay becomes negative (Figure 4c). Consequently, the lowest silt contents were measured in high clay soils, which also produced the lowest yields.

Data including all soil types with varying N fertilisation did not show a direct correlation between yields and SOC (Figures 2 and 5b) and soils with the highest SOC appeared to produce lower yields than soils with lower SOC (Figure 5b). Instead, a positive correlation was observed between clay content and SOC (Figure 4a). The absence of a significant relationship between yields and SOC in high clay soils reflects the negative relationship between yields and clay content in these soils (Figure 3a).

Among factors related to fertilisation and weather (including data from both 2017 and 2018), only N fertilisation level showed a positive correlation with yields ($r = 0.56$) (Figure 5a). No correlations were observed between P and K fertilisation levels and yields. Surprisingly, despite the very dry springs in 2016 and 2017, rainfall in May and June was negatively correlated with yield ($r = -0.35$). However, the effective temperature sum ($\sum$(T-5°C)) from May to August and rainfall from July to September were not significantly related to yield levels.

Regarding field management, higher yields were associated with crop rotation involving less than seven cereal crops in 10 years ($p = 0.040$), recent liming (within the last 10 years compared to liming over 20 years ago, $p = 0.009$), favourable field water regimes ($p = 0.008$), and the use of growth regulators ($p = 0.038$) and fungicides ($p = 0.018$) (Table S1: Data S4).

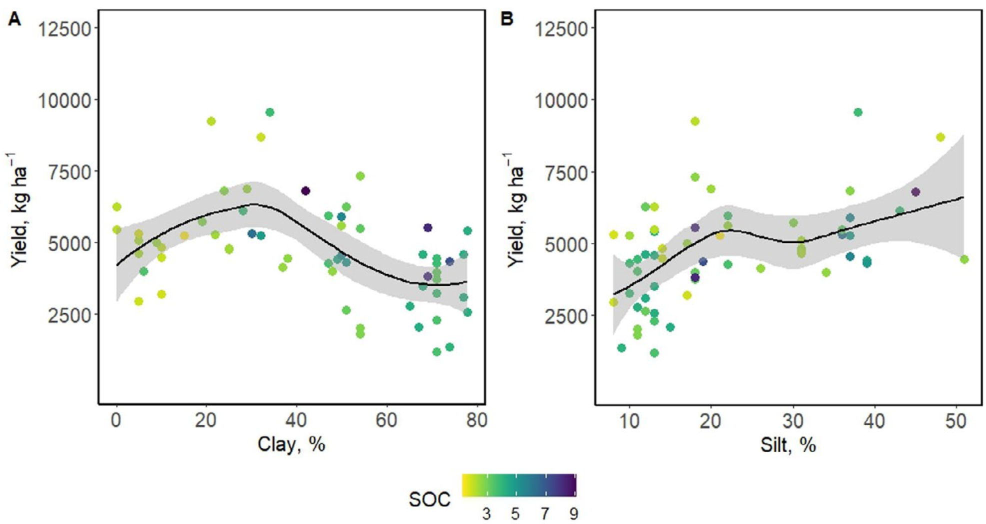

FIGURE 3 | Yields from 2016 and 2017 plotted against clay (A) and silt (B) contents with fitted least squares regression lines and 95% confidence intervals. The colour scale represents SOC content (%).

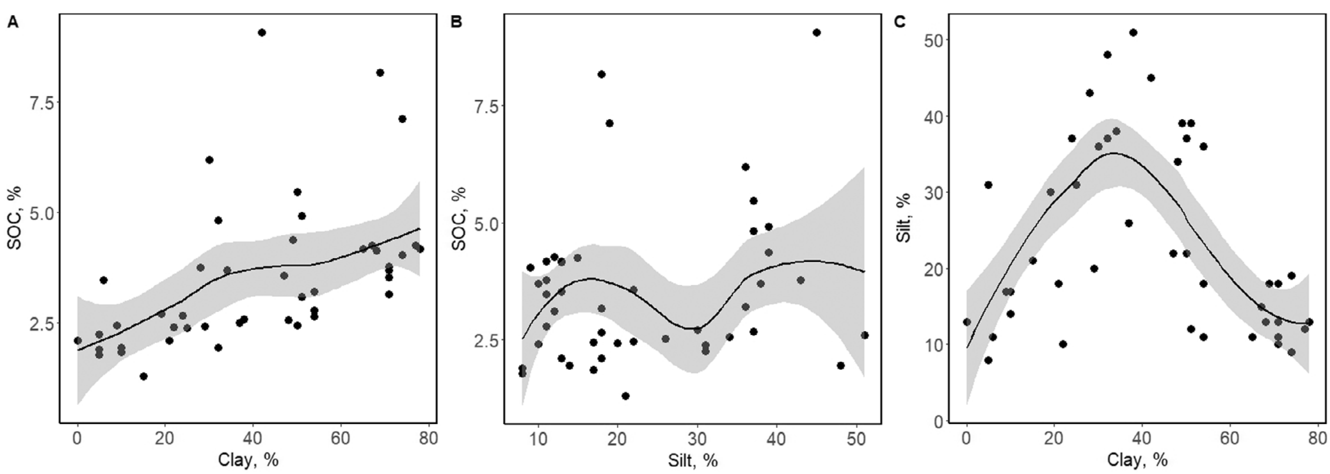

FIGURE 4 | Soil SOC content plotted against clay (A) and silt (B) contents, and silt content plotted against clay content (C) with fitted least squares regression lines and 95% confidence intervals.

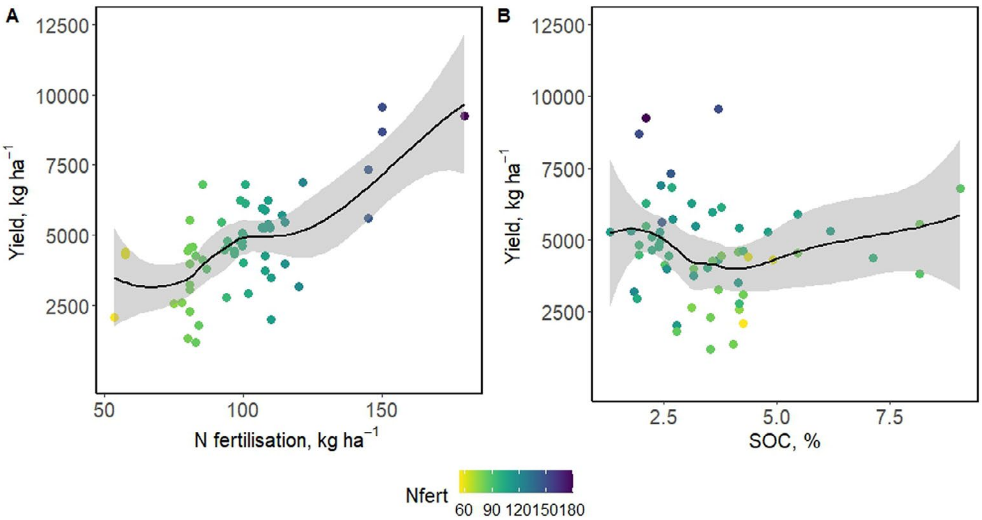

FIGURE 5 | Yields from 2016 and 2017 plotted against given N fertilisation (A), and SOC content (B), with fitted least squares regression lines and 95% confidence intervals. The colour scale represents N fertilisation (kg ha^{-1}).

Among these management factors, recent liming and the use of growth regulators and fungicides were slightly associated with higher N fertiliser rates ($p<0.10$, Table S1: Data S4). Higher N fertilisation is likely applied to fields with greater yield potential due to recent investments, such as liming. Additionally, measures to prevent fungal diseases contribute to realising this yield potential.

3.3 | Prediction Model for Grain Yield

Results from the mixed-effects prediction model for grain yield are presented in Table 3. Based on the mixed linear model, the estimated effect of SOC on grain yield was 342 ± 100 kg ha^{-1} per 1 percentage point increase in SOC ($p=0.0031$). Here, the positive effect of SOC on yield was clear, whereas clay content, the other soil parameter in the model, had a negative effect at clay contents above 40% (−33.9 kg ha^{-1} per 1 percentage point increase in clay, $p=0.0031$). Among field management parameters, the N fertilisation rate showed a significant positive effect on yield (56.6 ± 9.7 kg ha^{-1} per kg N ha^{-1} increase in fertilisation, $p<0.0001$). Although the inclusion of crop rotation improved model quality, the differences between rotations were not statistically significant.

In this dataset, barley yields were, on average, 1062 kg ha^{-1} higher than oat yields, whereas the mean wheat yields were 632 kg ha^{-1} higher than oat yields, though the latter difference was not statistically significant. Fitted and observed yields showed a reasonably good agreement across the observed yield distribution, as illustrated in Figure 6, with a conditional R^2-value of 0.83.

When yield history was included in the model, the estimated positive effect of a one percentage point increase in SOC on grain yield was 316 ± 92 kg ha^{-1} ($p=0.0035$). Clay content above 40% had a negative effect on yield (−42.0 ± 14.8 kg ha^{-1}, $p=0.0113$), whereas the effect of N fertiliser rate remained positive (48.2 ± 9.4 kg ha^{-1} per kg N ha^{-1}, $p<0.0001$). Yield history had an estimated effect of 0.399 ± 0.132 kg per kilogram of historical yield ($p=0.0076$). The conditional R^2-value for this model was 0.86, suggesting that the findings are robust and not sensitive to the model assumptions.

TABLE 3 | Results of the mixed linear model fit for the grain yield.

Variable	Estimate[a]	SE[a]	p[a]
Fixed effects			
Categorical			
Crops, kg DM ha^{-1}			
Intercept (Oat)	−2648	1164	0.0296*
Barley	1062	354	0.0077**
Wheat	632	381	0.1145
Crop rotation, kg DM ha^{-1}	601	409	0.1514
Continuous			
Fertilisation, kg DM kgN^{-1}	56.6	9.7	< 0.0001***
$Clay_{40}$, kg DM ha^{-1} clay(%)$^{-1}$	−33.9	15.7	0.0448*
SOC, kg DM ha^{-1} SOC(%)$^{-1}$	342	100	0.0031**
Random effects			
Block	$\sigma=783$		
Residual	$\sigma=735$		
Fit quality			
R^2_{mar}/R^2_{con} [b]	0.65/0.83		

Abbreviation: SE, Standard error.
[a]For the fixed effects $P<0.05$ (*), $p<0.01$ (**), $p<0.001$ (****).
[b]Marginal R^2-value/conditional R^2-value.

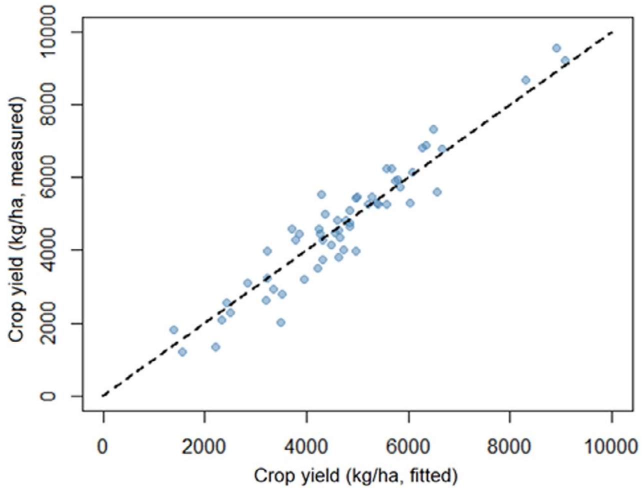

FIGURE 6 | Fitted versus observed crop yields.

4 | Discussion

The statistical model demonstrated a clear positive yield response to SOC with an estimated increase of 342 kg ha^{-1} ± 100 kg ha^{-1} per one percentage point increase in SOC. This response was observed when accounting for the most important effects of soil type (clay content) and crop management (N fertiliser rate). The estimated yield increase per one percentage point increase in SOC corresponds to approximately 10% of the national mean yield level, which remains relatively modest. At clay contents exceeding 40%, clay had a negative effect on yield, with the results suggesting that soils with 10 percentage points higher clay content require one percentage point higher SOC to achieve equivalent yields to lower-clay soils. Including the effect of different cereal crops reduced variation in the model but provided estimates that are more reflective of the dataset used than general yield levels of spring cereals cultivated in Finland. The statistical model exhibited a strong fit, with R^2-values of 0.83 and 0.86 with and without yield history, respectively.

During the two study years, the measured yield levels were generally higher than those reported for spring cereals in the Finnish official statistics for the study regions in 2016 and 2017 (Data S2; OSF 2018a). In 2016, two out of 15 fields yielded less than regional statistics, whereas in 2017, variability among fields increased, and ten out of 42 fields yielded less than the regional average values. In the official statistics, differences in average yield levels between cereal species were small, with yields generally decreasing towards central-eastern Finland.

The crop yield data in the present study showed interannual and regional variation. Contrary to national trends, the central-eastern region exhibited relatively high average barley yields compared to the southern inland regions in both years. In the southern coastal region, spring wheat was dominantly cultivated, and wheat yields were higher than in other regions. In both study years, May experienced exceptionally dry conditions. Early summer droughts have frequently caused irreversible decline in the yield potential of spring cereals under rainfed agriculture in Southern Finland (Peltonen-Sainio et al. 2021). Consequently, regional variation in average yield levels may partly reflect differences in precipitation patterns during critical periods of plant growth.

Many studies have explored the relationship between SOC and soil productivity (Lal 2020). Although some have reported no effect or even a decrease in yield with increased SOC (Kirchmann et al. 2020; Jordon et al. 2022), the majority show a positive association between SOC and crop yields. In a global meta-analysis, Oldfield et al. (2019) found that SOC increases crop yields up to concentrations of 2%, after which the positive relationship begins to level off. In a more recent European study, Campos-Cális et al. (2024) reported the positive effects of SOC on cereal yield to level off after 1.4%.

Boreal agricultural soils are typically rich in SOC with topsoil concentrations ranging from 2% to 5% (Heikkinen et al. 2022), exceeding the globally assessed critical limit of 2%. The present study suggests that under boreal conditions and in high clay soils, the SOC positively influences yield levels even in soils with relatively high SOC contents. Observed SOC levels in this study averaged 3.1% and were mostly above 2% (see Table 1, Figure 5). These findings align with those of Riley and Bakkegard (2006), who observed crop yield increases up to SOC concentrations of 6% in Norway. However, our results contrast with the findings of Kirchmann et al. (2020), who reported a negative association between SOC and yield in Sweden, despite a similar climate and soil type. Kirchmann et al. (2020) suggested that this negative relationship likely resulted from lower pH in SOC-rich soils. Similarly, a model-based study by Ghaley et al. (2018) in Denmark found that increased SOC contents benefited wheat yields only in nutrient-depleted soils. These findings highlight the importance of intercorrelations between SOC and other soil parameters in yield formation, as well as the need to consider climatic factors and soil texture when determining sufficient SOC levels for productive arable soils.

Clay minerals and clay-sized particles significantly contribute to soil CEC, supporting the retention and availability of cationic nutrients essential for soil fertility. However, according to our model, clay contents exceeding 40% have an increasingly negative effect on yields. This suggests that in soils with high clay content, the benefits of clay-sized particles are outweighed by other challenges. SOC supports soil productivity by serving as a major N reservoir. Microbial decomposition of SOM results in the continuous release of plant-available N (Jarvis et al. 1996). A laboratory incubation by Soinne et al. (2021) showed that N mineralization decreased with an increasing clay/SOC ratio, suggesting that clay content plays a significant role in regulating the availability of organic N for mineralization. Similarly, Soinne et al. (2021) reported that, in the absence of N fertilisation, fields with a high clay/SOC ratio produced lower yields than fields with a higher SOC relative to clay content. If the effect of SOC on soil productivity were solely due to its influence on N availability, then N fertilisation would be expected to compensate for yield losses in soils with a high clay/SOC ratio. However, even with N fertilisation, Soinne et al. (2021) found that these fields still produced lower yields. This indicates that other factors, such as poor soil structure associated with soils having a high clay/SOC, also contribute to reduced productivity.

In clay soils, textural porosity, defined by the pore space between primary particles, consists predominantly of micrometre-scale pores. According to Kutílek (2004), these submicroscopic pores can hinder the formation of water flow paths or clusters of fluid water molecules. Such pores are too small to support primary production, necessitating the development of a secondary (structural) pore system for clay soils to function effectively (Hajnos et al. 2006) Soil organic matter (SOM) plays a crucial role in the formation of these structural pores through aggregation and stabilisation of soil structure (Chaney and Swift 1984; Tisdall and Oades 1982; Soinne et al. 2016). Early-season drought or waterlogging (evaluated by either low (0–18.2 mm) or high (33.7–122.4 mm) rainfall 0–3 weeks after sowing) has been shown to have a clear negative effect on barley yields in Finnish weather conditions (Hakala et al. 2012). This sensitivity to precipitation after sowing is likely accentuated in clay soils with a pore system not supporting rapid infiltration and percolation. According to Soinne et al. (2023), in clay soils, the volume of pores that can be drained by gravity is positively related to SOC, indicating reduced risk of surface soil saturation in clay soils with high SOC. Furthermore, Soinne et al. (2016) previously demonstrated that higher clay content requires greater SOC to stabilise soil structure and reduce the dispersion of clay particles. Additionally, the clay-to-SOC ratio has been proposed as an indicator of soil quality and productivity (Dexter et al. 2008; Johannes et al. 2017; Prout et al. 2021; Soinne et al. 2021). These findings support our results, indicating that the relationship between SOC and yield is not straightforward. In fine-textured soils, higher SOC levels are needed to achieve productivity comparable to that of soils with lower clay content.

Among fertiliser nutrients, cereal yields typically exhibit the highest response to N fertilisers. In this dataset, the estimated yield response to N was 56.6 kg ha^{-1} per 1 kg of fertiliser N applied. This agronomic efficiency of N was higher than previously reported values, such as 20–30 kg DM ha^{-1} per 1 kg of N by Sylvester-Bradley and Kindred (2009) or 14–35 kg DM ha^{-1} per 1 kg of N reported by Muurinen et al. (2007). It is important to note, however, that in this study farmers had already optimised N application rates based on expected yields (yield history). Additionally, the use of inputs such as fungicides and growth regulators was often dependent on the anticipated production levels. Thus, N fertilisation rates reflect the farmers' expectations of field performance and are closely tied to other investments made to maintain or improve productivity. Furthermore, high N fertiliser rates are commonly used by Finnish farmers aiming to produce high-quality grains (Salo et al. 2007).

Many soils in the present study had relatively low plant-available P content in the plough layer. In a Norwegian survey, Grønlund et al. (2006) observed a positive relationship between soil test P content and crop yield, indicating P deficiency at low soil P levels. Similarly, in the present study, soil test P values were often below the threshold levels of 6 and 10 mg P_{aAAc} l^{-1} for clay and coarse-textured soils, respectively, below which a positive yield response to P fertilisation would be expected (Valkama et al. 2011). Nevertheless, no relationship was observed between soil test P and cereal yields. Consequently, soil test P did not appear to be a yield-limiting factor.

The crop rotation variable was retained in the statistical model as it improved the fit of the final model (Table 3), although its positive effect on cereal yields in this dataset was not statistically significant. Positive effects of diversified crop rotations on yields are well established under various growing conditions (e.g., Bowles et al. 2020; Dias et al. 2015; Jalli et al. 2021; Zhao et al. 2020). Yield increases associated with alternating crop rotations compared to monocultures or short rotations have been attributed to several factors, including improvements in soil structure, microbial activity and nutrient availability (particularly N), as well as reductions in insect pest pressure, plant diseases and weeds. Additionally, diverse rotations may mitigate the presence of growth promoting or inhibiting agents in the soil (Berzsenyi et al. 2000; Bullock 1992). Diverse crop rotations can also enhance yields through their impact on SOC, especially when perennial crops are included (Anderson-Teixeira et al. 2013; King and Blesh 2018; Sainju et al. 2017).

5 | Conclusions

Due to its extensive influence on soil functioning, SOC is expected to enhance the productivity of mineral agricultural soils. Previously, a positive relationship between yields and SOC has been observed at SOC concentrations up to 2%, beyond which the relationship begins to level off (Oldfield et al. 2019). However, under boreal conditions, our results indicate a positive relationship between yield levels and SOC even in soils with relatively high SOC contents (1.3%–9.1%). The estimated change in yield resulting from a one percentage point change in SOC was relatively modest, at 342 kg ha^{-1}, and overall, N fertilisation—positively associated with other management practices—emerged as the primary factor governing yield in these high-SOC soils. In soils with a clay content exceeding 40%, the positive effects of SOC on yields are reduced or may even be offset by the negative impact of the high clay content on soil productivity. Consequently, in fine-textured soils (clay > 40%), an additional percentage point of SOC is needed for every 10 percentage point increase in clay content to achieve the same productivity as soils with lower clay content. Our results highlight the importance of climatic factors and soil texture in determining sufficient SOC levels for productive arable mineral soils.

Acknowledgements

This study was funded by the Ministry of Agriculture and Forestry (Finland) as part of the project 'The role of organic matter in soil productivity' (ORANKI) and by Strategic Research Council (SRC) at the Research Council of Finland as part of the project 'Multi-benefit solutions to climate-smart agriculture' (MULTA, grant number 352435). We extend our gratitude to the technical staff of Luke Jokioinen and Maaninka for their seamless cooperation in field selection, management, and laboratory analyses. We also gratefully acknowledge the participating farmers for their valuable contributions. Open access publishing facilitated by Luonnonvarakeskus, as part of the Wiley - FinELib agreement.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.