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RESEARCH ARTICLE

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Response of maize yield to changes in soil organic matter in a Swedish long-term experiment

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Abstract

Agricultural practices that lead to soil carbon sequestration may be a win–win strategy for mitigating global warming and improving soil fertility and resource use efficiency. The mechanisms through which soil organic carbon (SOC) concentration affects crop yields are numerous but difficult to separate. The objective of this study was to disentangle these processes and estimate to what extent the yield response to SOC is mainly driven by changes in physical or biochemical properties and processes. This was achieved by analysing the response of yields in continuous maize to SOC concentrations during 20 years (2000–2019), which had evolved in 14 experimental treatments in a Swedish long-term field experiment at Ultuna since 1956, ranging from 0.94% to 3.65% in the topsoil (0–20 cm). Average maize yields during this period varied between 1.9 and 8.4 Mg dry mass per hectare in the different treatments. The treatments comprise applications of different mineral nitrogen (N) fertilizers and organic amendments and combinations thereof. Our analysis showed that maize yield in the treatments that were not severely limited by nitrogen supply or soil acidity increased by 16% for each percentage unit increase in SOC. We applied the widely used concept of critical N concentration in plant biomass to diagnose the N status in maize in the different treatments (N nutrition index [NNI]) and parameterized a response function between yield and pH (R_{pH}). Dry soil bulk density (BD) was used as a proxy for soil physical properties. These three variables NNI, R_{pH} and BD explained 95% of the variation in maize yields among treatments. Further analysis of the relationship between BD, SOC and plant available water capacity revealed that about two thirds of the yield increases in response to SOC change could be ascribed to associated changes in soil physical properties. Our analysis suggests that the extra storage capacity of water, which increased by up to 15 mm in the topsoil for each unit percentage increase in SOC, was the main driver for the observed yield responses. We conclude that measures for increasing SOC in soils most likely are an effective adaptation strategy for reducing the risk of crop damage during dry spells, which probably are becoming more frequent in the future due to climate change, even in relatively humid climates as in Sweden.

KEYWORDS

crop productivity, maize, nitrogen nutrition index, nitrogen use efficiency, plant available water capacity, soil carbon, soil carbon sequestration, soil physical properties

1 | INTRODUCTION

Humanity is facing significant challenges such as climate change, food security, loss of biodiversity and depletion of natural resources. These challenges are interconnected and involve multiple trade-offs and synergies. Due to direct and indirect links to all these challenges, soils, land use and agricultural practices have come into focus in society. Various policies, programmes (such as the 4 per 1000 initiative; Minasny et al., 2017) and carbon farming schemes are currently being developed and implemented to promote soil health and climate change mitigation (European Commission, 2021). Soil carbon sequestration (SCS) has gained recognition as a win–win strategy and remedy for climate change adaption and mitigation as well as for restoring soil health, crop productivity and more efficient use of natural resources (IPCC WG1, 2021).

Agricultural practices that diversify crop rotations by including cover crops, and perennial plants or promote C inputs to the soil in other ways have been found to increase soil organic carbon (SOC) and soil organic matter stocks (Kätterer & Bolinder, 2022). This can lead to SCS, that is, the net transfer of carbon from the atmosphere to the soil (Don et al., 2023), which, in turn, may increase yield potentials, improve food security, the efficiency of agricultural inputs and promote the efficient use of soil, one of our primary natural resources (Rumpel et al., 2020). It was estimated that 0.08–0.4 Pg C year^{-1} or even more if further technical development in plant breeding is considered, can be globally sequestered in upland agricultural soils (Paustian et al., 2016). On considering only low-cost measures, Bossio et al. (2020) estimated potential SCS to be 0.14 Pg C, which corresponds to about 0.1 Mg C ha^{-1} year^{-1} (Kätterer & Bolinder, 2022). Although the magnitude of potential SCS is highly uncertain and disputed due to methodological inaccuracies, nutrient limitations or socioeconomic barriers (Moinet et al., 2024; Poulton et al., 2018; Van Groenigen et al., 2017), the implementation of practices that increase soil carbon storage can contribute to achieving several Sustainable Development Goals related to climate change, reduced hunger, poverty and increased environmental protection (Soussana et al., 2019).

The positive relationship between SOC and crop productivity has been acknowledged for a long time (Manlay et al., 2007). This is not surprising since SOC is a master indicator for soil quality and soil functioning (Bünemann et al., 2018) contributing to at least 12 of the 17 Sustainable Development Goals of the United Nations (Kopittke et al., 2022). Already small increases in SOC at a global scale have been estimated to enhance farmers' output during drought years while reducing global temperature warming (Iizumi & Wagai, 2019). The mechanisms through which SOC affects crop biomass production are numerous (Jha et al., 2023; Johnston et al., 2009; Meurer, Barron, et al., 2020; Rubio et al., 2021; Schjønning et al., 2012). They include biogeochemical processes such as increased turnover and supply of nutrients to plants from the mineralization of soil organic matter, and enhanced retention of nutrients through increased cation exchange capacity, as well as physical processes such as better water infiltration, soil structure and structural stability due to stronger aggregation leading to less soil erosion, alleviation of compaction, facilitation of root growth, increased water storage and diffusivity of gases. Although SOC accumulation in agricultural soils is predominantly beneficial, potential trade-offs have to be accounted for. For example, higher SOC stocks may result in increased nitrate leaching (Powlson et al., 1989) and N_2O emissions (Guenet et al., 2021). Thus, certain SCS-supporting management practices may offset some of the benefits of SCS.

Highlights

- Maize yield responses to SOC were studied in a field trial with clay soil in a hemiboreal climate
- Yields increased by 14%–16% for each unit percentage of SOC increase
- About two thirds of the yield response was likely due to improved soil physical properties

Several meta-analyses assessing the relationship between SOC and crop yields have been published in recent years. Oldfield et al. (2019) presented global-level predictions for crop yields in response to changes in SOC. Based on their meta-analysis, they estimated potential yield increases of 10 ± 11% for maize and 23 ± 37% for wheat amounting to 32% of the projected yield gap for maize and 60% of that for wheat. Moinet et al. (2023) presented an insightful review on this topic in which they analysed 21 publications including 36 meta-analyses based on global, continental (four continents) or national datasets. The majority (17) of these reported positive relationships between SOC and crop yield, 12 reported no effect and 7 reported negative relationships. Although the response was positive in most cases, Moinet et al. (2023) concluded that the outcomes are context-specific and vary with space, time and methods used. They also elaborated on the validity and limitations of these meta-analyses, addressing problems regarding the causality between SOC and crop yields and highlighting differences in the choice of response variables, for example, actual or potential yields. Indeed, confounding factors and potential biases make this kind of analysis difficult, even under similar climatic conditions.

This is illustrated in two Scandinavian studies, where negative correlations between SOC and crop yields were found at the national scale in Denmark (Oelofse et al., 2015; Schjønning et al., 2018) and Sweden (Kirchmann et al., 2020), and potential confounding factors were discussed. For example, perennial ley is a major crop on dairy and these farms have higher SOC compared to farms growing annual cash crops only (Henryson et al., 2022). Since their focus is on milk production, dairy farmers may be less focused on optimizing yields of their grain crops which also are part of their rotations. Consequently, grain crop yields on dairy farms may be lower than on farms with only annual crops, which results in a negative correlation between SOC and yields (Schjønning et al., 2018). Moreover, leys take up far more cations than anions, leading to stronger acidification in leys compared with cereals (Haynes, 1983). Liming, to compensate for this loss of cations, may be less frequent on dairy than on cash crop farms, which would enforce a negative correlation between SOC and crop yield. Systematic differences in soil conditions between farming systems may also affect this relationship since dairy farms are generally located in areas with poorer, more acidic soils than cash crop farms. In fact, a significant negative correlation between SOC and soil pH was found in a Swedish national dataset (Kirchmann et al., 2020). Kirchmann et al. (2020) concluded that low soil pH rather than high SOC was the most probable reason for the observed yield decline with increasing SOC. Thus, a proper analysis of the relationship between SOC and crop yields needs to account for this potential interaction with other yield-determining variables.

Although the cycling of nutrients increases with SOC, since nutrient limitations and acidity can be controlled by fertilizer and lime, the huge interest in the relationship between SOC and soil fertility is mainly driven by non-nutrient-constrained yield effects (Hijbeek et al., 2017). These effects relate to soil physical properties and associated processes. For instance, the effect of SOC on plant-available water capacity (PAWC) has been investigated in many studies as reviewed by Lal (2020). Whereas most of the studies he reviewed reported a positive relationship between SOC and PAWC, several studies reported no or even negative correlations. He concluded that further research is needed to understand the mechanisms behind this relationship that can explain the huge variation among studies.

Our objective was to analyse the response of biomass production during the recent 20 years (2000–2019) to changes in SOC content that had evolved in 14 treatments in the 'Ultuna long-term soil organic matter experiment' in Sweden for more than five decades. In particular, we wanted to disentangle the processes behind this response, that is, to which extent the yield response due to SOC changes was mainly driven by changes in physical or biochemical properties and processes. We also analysed changes in soil acidity and crop N supply resulting from the long-term addition of mineral N fertilizers and organic amendments. We present new primary data from the experiment and studied yields of silage maize that was grown as monoculture since 2000 in response to changes in soil properties. After about five decades, SOC concentrations differed by almost a factor of four between the extreme treatments (Kätterer et al., 2011). This wide range of SOC concentrations established at the same site, is, except for a few other studies (Kauer et al., 2019; Lal, 2013), unique and suitable for this kind of analysis since it minimizes the potential interference with confounding factors related to different sites (Moinet et al., 2023). By considering N limitation and soil acidity in our analysis, we estimated the yield response to a change in SOC that is governed by soil structure and plant-accessible water and that cannot be compensated for by applying more mineral fertilizer.

We hypothesized that biomass production increases with SOC concentration due to higher N delivery from the soil and crop N use efficiency, as well as changes in soil physical properties affecting plant available soil water capacity. The positive response of crop productivity to increasing pH in acid soils is not new, but we intended to quantify this relationship along the range of pH-values in the treatments (4.18–7.27). Such high differences in soil pH are unique in studies on agricultural practices at the same site, and we hypothesized that productivity continues to increase with soil pH at pH-values above 6.5, which is the target value for clayey arable soils according to Swedish recommendations (Kirchmann et al., 2020).

2 | MATERIALS AND METHODS

2.1 | Site description and treatments

The Ultuna long-term 'soil organic matter experiment' (FRAME-56) was initiated in 1956 at the Swedish University of Agricultural Sciences (SLU) close to Uppsala

(59.82 °N, 17.65 °E). The major objective of the experiment is to investigate the long-term effect of different mineral N fertilizers and organic amendments on crop productivity and soil properties. The site lies within a Dfb climate (warm summer hemiboreal) according to the Köppen classification (Peel et al., 2007), with a mean annual (1956–2009) air temperature of 5.8°C and an annual mean total precipitation of 542 mm (Kätterer et al., 2011). The soil is classified as Eutric Cambisol (IUSS Working Group, 2006). The parent material consists of post-glacial sediments and illite is the main clay mineral (Gerzabek et al., 1997). In 1956, the topsoil (0–20 cm) had an organic C content of 1.50%, an N content of 0.17%, a pH (water) of 6.54 and dry soil bulk density (BD) of 1.44 Mg m^{-3}. The texture of the topsoil is clay loam with 36.5% clay, 41.0% silt (0.002–0.06 mm) and 22.5% sand (0.06–2 mm).

The experimental design consists of 15 treatments with four replicate plots in a randomized block design (Table 1). Each plot is 2 × 2 m, separated by 40 cm high steel frames extending to a depth of about 30 cm. Soil dry BD differs widely across treatments, which is reflected in elevation differences between the plots which varied by up to 5.7–7.5 cm between treatments (due to soil volume expansion with decreasing BD), depending on the two estimation methods used (Kätterer et al., 2011). Three of the treatments receive different types of inorganic N fertilizers only (80 kg N ha^{-1} $year^{-1}$), six receive organic amendments only, four receive both N fertilizer and organic amendments, and one receives neither N fertilizer nor organic amendments. A bare fallow, without any crop, is also included (Table 1). All plots are regularly weeded by hand or, during a few years with heavy weed invasion, treated with an herbicide. Weed biomass production has not been measured, but was estimated to be less than 50 kg dry matter ha^{-1} $year^{-1}$ (Kätterer et al., 2011).

In 10 of the treatments receiving different organic amendments, such as straw, green manure, farmyard manure, sawdust, peat and sewage sludge (SS), approximately the same amount of C (4 Mg ha^{-1}) was added in 1956, 1960, and biannually since 1963 after crop harvest before autumn tillage (Table 1). All organic amendments were produced ex situ, including straw and green manure. From 1956 to 1999, annual C3 crops were cultivated, whereof spring barley and oats were most frequent (see Kätterer et al., 2011 for details). Since 2000, silage maize, a plant with a C4 photosynthetic cycle, is grown every year. The rationale for this shift in crop type was to change the ^{13}C signature of SOC, which can be used to track the fate of maize-derived C in SOC (Menichetti et al., 2013, 2015) and in different soil fractions (Ghafoor et al., 2017), as respired CO_2 (Shahbaz et al., 2019) or in microbial biomass (Börjesson et al., 2016; Shahbaz et al., 2020). At harvest, all above-ground crop residues are removed after cutting the crops at the soil surface. Thus, crop residue inputs are solely from below-ground, including below-ground stem bases, root tissues and rhizodeposits. Thereafter, usually in October, the soil is tilled by hand with a spade to a depth of 20 cm. The effect on topsoil mixing is similar to that of mouldboard ploughing but soil compaction by heavy machinery is avoided. In spring, all plots are fertilized with the same amount of P and K, that is, 20 kg P ha^{-1} $year^{-1}$ as superphosphate and 35–38 kg K ha^{-1} as KCl with the intention that P and K should not limit plant growth. This was followed up with bi-annual soil tests showing very good P- and K-status in all treatments (data not shown). A more detailed description of the experiment and results for the first 35 years was presented by Kirchmann et al. (1994) and Persson and Kirchmann (1994) and for the first 53 years by Kätterer et al. (2011).

2.2 | Biomass and soil sampling and analysis

In this work, we focus on the period 2000–2019 when maize was grown, which has been sown in rows with a 40 cm distance. For estimating the dry mass of above-ground biomass, an area of 1.6 m^2 (0.8 × 2.0 m) in the centre of each plot was harvested, dried and weighed. Subsamples were analysed for N and other nutrients using standard methods and thereafter stored in our sample archive at SLU.

The soil was sampled at five random locations in each plot to a depth of 20 cm using a soil corer. Soil sampling was conducted after crop harvest but before tillage in autumn. The soil was sampled intermittently between 1956 and 1983, and biannually thereafter. The most recent sampling was done in 2019. The five samples per plot were then combined into one composite sample per plot before drying at 105°C and sieving at 2 mm. Soil C and N concentrations were measured with dry combustion (LECO instruments) and soil pH was measured in water. After analysis for plant nutrients, soil samples were then stored in our sample archive at SLU. The development of SOC concentrations in the treatments over time is presented in Figure 1, and average soil pH values over the period 1999–2019 per treatment are presented in Table 1. The BD was measured only occasionally in this experiment. Here, we use the measurements from 2009 that have been published by Kätterer et al. (2011) that were assumed to be representative of the period 2000–2019.

TABLE 1 Treatments in the Ultuna long-term soil organic matter experiment.

ID	Ref[§]	Treatment	Fertilizer[§§] (80 kg N ha^{-1} year^{-1})	Amendment (C/N ratio)	Yield (Mg ha^{-1})	SOC (%)	SON (%)	SOC/SON	BD (Mg m^{-3})	pH(H_2O)	R_{pH}	NNI
BF	A	Bare fallow				0.94^{L}	0.094	10.0^{de}	1.43	6.21^{de}		
Unf	B	Control			2.61^{fg}	1.09^{k}	0.106^{g}	10.3^{de}	1.40	6.30^{d}	0.99	0.52^{ef}
CaN	C	Calcium nitrate	$Ca(NO_3)_2$		6.07^{cd}	1.33^{i}	0.127^{f}	10.4^{d}	1.28	6.67^{b}	1.01	0.84^{abc}
AS	D	Ammonium sulphate	$(NH_4)_2SO_4$		1.92^{g}	1.20^{j}	0.136^{e}	8.85^{f}	1.21	4.18^{h}	0.30	0.65^{de}
CN	E	Calcium cyanamide	$CaCN_2$		6.26^{cd}	1.40^{h}	0.135^{e}	10.4^{d}	1.25	7.28^{a}	1.03	0.82^{abc}
GM	H	Green manure		Grass (33)	5.35^{de}	1.56^{f}	0.150^{d}	10.4^{d}	1.34	6.09^{de}	0.98	0.74^{cd}
SS	O	Sewage sludge		Sew. Sludge (8)	7.62^{ab}	2.66^{c}	0.274^{a}	9.71^{e}	1.02	4.90^{g}	0.82	0.94^{a}
FYM	J	Farmyard manure		Manure (14)	7.20^{bc}	2.12^{d}	0.202^{b}	10.5^{cd}	1.24	6.55^{bc}	1.00	0.79^{bc}
FYM + P[§§§]	K	Farmyard manure	Extra P	Manure (14)	7.12^{bc}	2.16^{d}	0.203^{b}	10.6^{cd}	1.20	6.35^{d}	0.99	0.80^{bc}
Peat	I	Peat		Peat (45)	4.52^{e}	3.10^{b}	0.170^{c}	18.2^{a}	1.12	5.62^{f}	0.94	0.55^{ef}
Peat+N	M	Peat +N	$Ca(NO_3)_2$	Peat (45)	8.38^{a}	3.65^{a}	0.204^{b}	17.9^{a}	1.05	5.99^{e}	0.97	0.89^{ab}
SD	L	Sawdust		Sawdust (1865)	2.58^{fg}	1.82^{e}	0.129^{ef}	14.1^{b}	1.28	6.37^{cd}	0.99	0.50^{f}
SD + N	N	Sawdust +N	$Ca(NO_3)_2$	Sawdust (1865)	6.98^{bc}	2.15^{d}	0.158^{d}	13.6^{b}	1.23	6.70^{b}	1.01	0.79^{bcd}
Str	F	Straw		Straw (74)	3.49^{ef}	1.48^{g}	0.134^{e}	11.1^{c}	1.38	6.39^{cd}	0.99	0.58^{ef}
Str + N	G	Straw +N	$Ca(NO_3)_2$	Straw (74)	7.09^{bc}	1.88^{e}	0.170^{c}	11.1^{c}	1.21	6.60^{b}	1.00	0.86^{abc}

Note: Type of N fertilizer and organic amendments (with C/N ratio in parenthesis), measured dry matter yields of silage maize, soil organic carbon (SOC) and nitrogen (SON) concentrations, soil C/N ratios, dry soil bulk density (BD), pH in water, and estimated relative growth response to pH (R_{pH}), and nitrogen nutrition index (*NNI*). Values represent average values for the period 2000–2019 calculated from annual yields and biannual soil sampling conducted in autumn after harvest, except for BD which was measured only once, in 2009, during this period and for which average values were taken from Kätterer et al. (2011). Means suffixed by different letters are significantly different at $p < 0.05$ according to Tukey's Studentized range test.

[§]Reference to treatment IDs used in previous publications from the Ultuna trial.

[§§]All treatments including the bare fallow receive 20 kg P and 35–38 kg K ha^{-1} year^{-1}.

[§§§]Calcium cyanamide was applied in FYM + P only in 1956. Manures applied in 1956 and 1960 derived from different batches in FYM and FYM + P. Total applications of N as manure were about 60 kg higher in FYM + P than FYM during that period. Thereafter, the only differences between FYM and FYM + P were double P-application (superphosphate) in FYM + P compared to FYM and all other treatments.

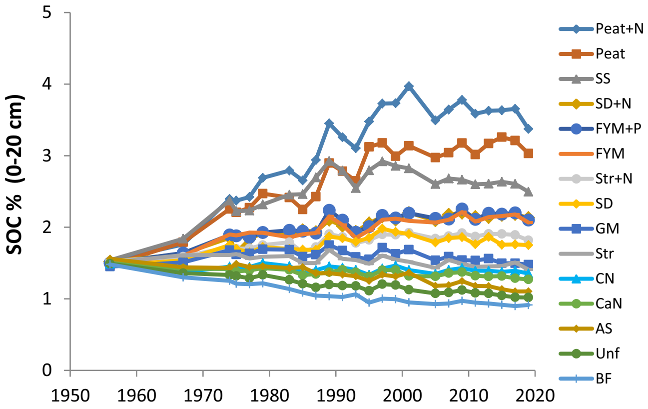

FIGURE 1 Topsoil (0–20 cm) carbon concentrations over time (1956–2019) for the 15 treatments in the Ultuna frame trial (see Table 1 for the description of treatments).

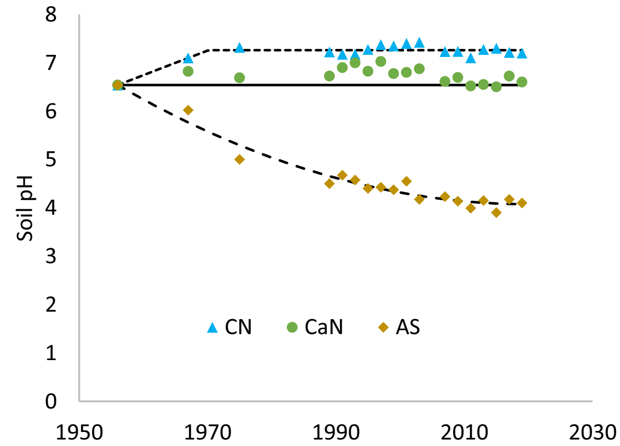

FIGURE 2 Evolution of soil pH(H_2O) over time in treatments CaN, AS and CN. The fitted trend lines are for treatments CaN: $y = 6.54$, AS: $y = 0.000599x^2–0.0769x + 6.54$, CN: $y = \text{Min}(6.54 + 0.051x; 7.26)$ for $x = (\text{year-1956})$.

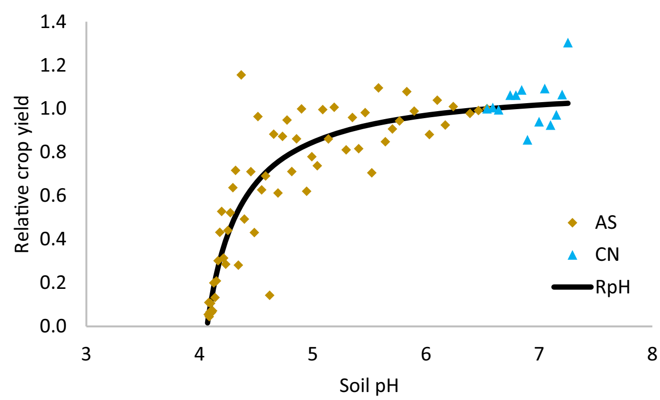

FIGURE 3 Yields in treatments AS and CN relative to those in treatment CaN, which had a relatively stable pH of 6.54. The estimated parameter values are $R_{max} = 1.12$, $R_0 = 4.07$, $K = 0.31$, and the calibrated response function is: $R_{pH} = 1.12(\text{pH} - 4.07)/[0.31 + (\text{pH} - 4.07)]$.

2.3 | Yield response to changes in SOC

As N supply differed among experimental treatments, which also altered soil pH over time (Table 1), we grouped the treatments into five classes:

i. *High N treatments*, being those eight treatments receiving 80 kg N ha^{-1} $year^{-1}$ from mineral fertilizer (CaN, CN, Peat+N, SD + N and Str + N) as well as those receiving more than 80 kg N ha^{-1} $year^{-1}$ from organic N inputs (FYM, FYM + P and SS), 140 or 250 kg N ha^{-1} $year^{-1}$ from manure or SS, respectively,
ii. *Low pH treatment* AS with an average soil pH value of 4.18, where toxic effects of Al^{3+} are likely severe (Rahman & Upadhyaya, 2021),
iii. *Medium N treatment*, that is, treatment GM that receives 61 kg N ha^{-1} $year^{-1}$ from green manure and is, therefore, moderately N limited,
iv. *Low N treatments*, that is, the unfertilized control treatment (Unf) and those receiving organic inputs with low N content, such as cereal straw (Str) and peat (Peat) corresponding to 27 and 44 kg N ha^{-1} $year^{-1}$, respectively, and
v. *Very low N treatment*, that is, treatment SD, where sawdust is added with a C/N ratio as high as 1865, which likely causes N immobilization during decomposition.

2.4 | Yield response to soil pH

For evaluating the effect of soil pH on crop yield, we considered the three treatments CaN, AS and CN that received the same amounts (80 kg N ha^{-1} $year^{-1}$) but different types of mineral fertilizers, which over time resulted in the evolution of significantly different soil pH values (Table 1). We used the whole time series (1956–2019) to cover the entire range of soil pH differences between treatments. Since soil pH measurements were scarce during the first three decades of the time series, we fitted trend lines to the data series to obtain annual soil pH estimates. They described the data well, especially for the recent two decades which are in focus in this paper (Figure 2). In treatment CaN, soil pH was quite stable over time. Thereafter, we normalized annual yield records in AS and CN relative to those in CaN by calculating yield ratios, that is, AS/CaN and CN/CaN. This allowed us to construct response functions describing the relationship between annual yield measurements as a function of soil pH (Figure 3). The response of these yield ratios to soil pH (R_{pH}) was then plotted and a Michaelis Menton-type function was fitted to the data by estimating the value of its three parameters by minimizing root mean square error using the generalized reduced gradient function implemented in the solver package in MS Excel:

$$R_{\mathrm{pH}} = \frac{R_{\max}\,(\mathrm{pH} - R_0)}{K + (\mathrm{pH} - R_0)}, \text{for } R_0 \leq \mathrm{pH} \leq 7.26, \quad (1)$$

where $R_{\max}$ defines the asymptote of the function, R_0 is the intercept on the x-axis corresponding to the soil pH below which crop growth will vanish and K is a fitting parameter. The sum of $K + R_0$ corresponds to the soil pH at which biomass production is expected to be 50% compared with the reference pH, which here corresponds to the initial soil pH (6.54). The function is probably only valid in the range of soil pH values considered here, that is, from R_0 to pH 7.26, representing the average value in treatment CN during the period 1999–2019.

2.5 | Nitrogen nutrition index

We applied the widely used concept of critical N concentration (N_c) to diagnose the N status in maize in the different treatments (Liu et al., 2023). This concept builds on the principle that plant N concentration decreases monotonically as the crop grows (Greenwood et al., 1986), and N_c is defined as the minimum N concentration required for maximum crop growth rate under given conditions (Ulrich, 1952). A lot of work has been done to develop empirical functions describing N_c for different crops during the vegetative growth of agricultural crops (Greenwood et al., 1986; Lemaire et al., 2008). We adapted here the empirical power function developed for a German dataset that was shown to be valid even until silage maturity (Herrmann & Taube, 2004):

$$N_c = 3.41 \cdot \mathrm{DM}^{-0.391}, \quad (2)$$

for maize dry mass (DM) ≥1 Mg ha^{-1} and $N_c = 3.41$ for DM <1 Mg ha^{-1}. The rationale for a constant N_c at low biomass is that light competition for isolated young plants is limited during early growth stages (Plénet & Lemaire, 1999). Under these conditions, internal nitrogen concentration is linearly related to the relative growth rate and exponential growth occurs if the internal concentration is constant (Ågren, 1985; Ingestad, 1982). To quantify the degree of N limitation, we calculated the N nutrition index (*NNI*) according to Lemaire et al. (2008) from the ratio of actual N concentration in maize biomass (N_a) relative to N_c,

$$NNI = N_a / N_c. \quad (3)$$

NNI reflects the degree of N limitation that is proportional to plant growth or yield, it varies between 0 and an upper limit of 1.0, that is, when $N_a > N_c$, the nitrogen supply has been in excess and will not result in further plant growth.

2.6 | Nitrogen balances

Nitrogen balance components were compiled to gain knowledge about the use efficiency of N in fertilizers and organic amendments in the different treatments and their potential impact on the environment. Nitrogen in harvested biomass was calculated from annual records of DM yield and N concentrations. Nitrogen added in the organic amendments was calculated from bi-annual measurements for the period from 1999 to 2019. Air deposition estimates were adapted from Pihl Karlsson et al. (2012). Changes in soil organic N (SON) stock to a depth of 20 cm were calculated from the slope of linear regression lines fitted to bi-annual SON concentrations (1999–2019), multiplied by BD measured in 2009 (Kätterer et al., 2011). The changes in SON stocks were included in our analysis because they constitute important sinks or sources in N balances (Karlsson et al., 2003). The N surplus, a widely used indicator for potential N losses to the environment, was calculated as the difference between measured N inputs from fertilizer, seeds and air deposition, and outputs in the harvested DM. As indicators of resource use efficiency (outputs/inputs), we calculated several commonly used indicators (Lahda et al., 2005) of nitrogen use efficiency (NUE) by excluding (NUE) or including (NUE*) net annual changes in SON (i.e., N mining). We also calculated fertilizer agronomic efficiency (AE), which is the difference in harvested N in treatment and unfertilized control over inputs (excluding changes in SON). In addition, we calculated fertilizer use efficiency (FUE) accounting for differences in harvested N (h) and soil N mining (m) between the fertilized treatment (subscript t) and the corresponding unfertilized control treatment (subscript c): $[(h_t–h_c)–(m_t–m_c)]$ divided by annual fertilizer input (80 kg N ha^{-1}). Control treatments were those with corresponding amendments, that is, CaN for treatments AS and CN, Str for Str + N, Peat for Peat+N and SD for treatment SD + N. For the treatments receiving amendments but no mineral N, we calculated amendment N use efficiency (AUE) in the same way as FUE but with annual N input from organic amendments in the denominator. The control treatment here was always the unfertilized control (Unf). By comparing FUE and AUE, the equivalent N fertilizer value of organic amendments can be calculated (Delin et al., 2012).

2.7 | Calculation of plant available water capacity

Soil water retention characteristics were measured in 1997 in the topsoil (0–20 cm) in nine treatments (BF, Unf, CaN, Str, GM, Peat, FYM, SD and SS) in the wetter range up to a tension of pF 3.5, corresponding to the pressure of a 30 m water column (Kirchmann & Gerzabek, 1999). Assuming that water content at wilting point (pF 4.2) was not responsive to experimental treatments, we used the measurement of wilting point from a soil profile in 1969 adjacent to the experimental plots (17.2%; Wiklert et al., 1983) to calculate PAWC, that is, the difference in volumetric soil water content between field capacity (pF 2) and wilting point (pF 4.2).

2.8 | Data analysis

The variance of target variables such as yield, SOC, SON, soil pH and *NNI* measured during the two decades was analysed using mixed models in the SAS software (SAS Institute Inc., Cary, NC, USA). For yields, plot-wise annual records for the period 2000–2019 were available. Treatment was included in the statistical model as a fixed categorical variable, replicate block as a random factor and year as a repeated measure. *NNI* was calculated per treatment and year since plot-wise N concentrations in maize biomass were not available for all years. For the soil variables, bi-annual measurements of SOC, SON and soil pH were available (except for 2003) at the plot scale. The same statistical model as for yields was applied to these soil variables, but the sampling year was defined as a numerical variable instead of a repeated measure to cover potential trends over time. Interactions between sampling year and treatment were significant for SOC and SON and were further studied with linear regressions fitted to the times series of SOC and SON for each treatment. For soil pH, this interaction was not significant and therefore excluded from the model. Tukey's Studentized range test was used to analyse treatment effects. Multiple linear regression analysis was used for stepwise testing the impact of BD, R_{pH} and *NNI* on average maize yield (2000–2019) in the treatments.

3 | RESULTS AND DISCUSSION

3.1 | Yield response to changes in SOC

Maize DM yields varied between 1.85 and 8.39 Mg ha^{-1} across years in the different treatments. Treatment effects on yield were significant and differences between several treatments were significant according to Tukey's post hoc test (Table 1). Replicate block and interactions with treatment and sampling year had no significant effect on the variance in crop yield according to the mixed model. Maize yield increased with SOC in both the 'High N treatments' and 'Low N treatments' (Figure 4). Yields in treatment Peat+N with the highest SOC concentration (3.67%; Table 1) were 39% higher than those in treatment CaN (with 1.33% SOC) receiving only nitrate fertilizer. The yield response to SOC was about 1 Mg ha^{-1} for each percentage unit increase in SOC in the 'High N treatments' and about 0.9 Mg ha^{-1} in the 'Low N treatments' according to linear regression analysis ($R^2 = 0.96$). In relative terms, this corresponds to a yield increase of 16% per unit of SOC% increase. This yield response can probably not be extrapolated ad infinitum, but surprisingly, the yield response to SOC in this study was linear up to 3.67% SOC and did not level off above 2% SOC as suggested by the meta-analysis presented by Oldfield et al. (2019).

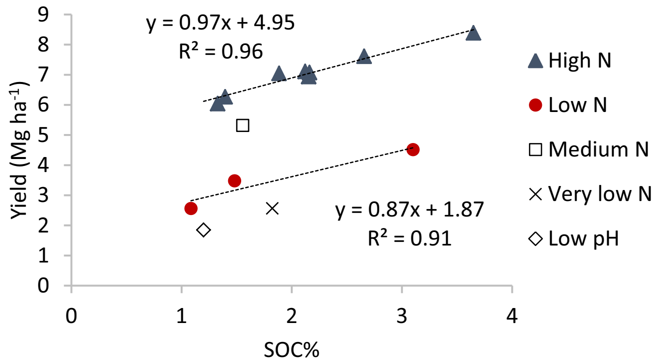

FIGURE 4 Maize yield response to SOC concentration averaged over 20 years (2000–2019 for yields and 1999–2019 for SOC) for the experimental treatments grouped into five classes depending on N supply and soil pH (see text and tables for details). The lines are response functions fitted to the eight 'High N treatments' (CaN, CN, Str + N, FYM, FYM + P, SD + N, Peat+N and SS) and three 'Low N treatments' (Unf, Str and Peat).

3.2 | Yield response to soil pH

Fertilization with calcium nitrate could maintain soil pH in treatment C throughout the experiment (Figure 2). Values of soil pH during the recent decade (6.60) were similar to the initial pH in 1956 (6.54). Fertilization with calcium cyanamide (treatment CN), which is hydrolysed in the soil to form cyanamide and bicarbonate, increased soil pH during the first two decades by about 0.7 pH units to 7.26. On the contrary, fertilization with ammonium sulphate in treatment AS strongly acidified the soil over time (Figure 2), where the soil pH has dropped to values

TABLE 2 Nitrogen balance components (kg N ha^{-1} $year^{-1}$) and efficiency indices (%) in the experimental treatments for the period 2000–2019.

	BF	Unf	CaN	AS	CN	GM	SS	FYM	FYM + P	Peat	Peat+N	SD	SD + N	Str	Str + N
Harvested biomass (kg N ha^{-1} $year^{-1}$)		27.9	79.8	29.9	80.5	66.4	116	86.6	88.4	45.4	106	27.3	84.2	39.1	91.3
Mineral fertilizer (kg N ha^{-1} $year^{-1}$)			80	80	80						80		80		80
Amendments (kg N ha^{-1} $year^{-1}$)						61	250	140	140	44	44	1	1	27	27
Seeds[a] (kg N ha^{-1} $year^{-1}$)		0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Air deposition[b] (kg N ha^{-1} $year^{-1}$)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
N mining[c] (kg N ha^{-1} $year^{-1}$)	25	32	27	17	22	42	28	10	10	14	32	32	28	29	29
Total inputs[d] (kg N ha^{-1} $year^{-1}$)	28	35	110	100	105	107	281	152	153	62	160	36	112	59	139
N surplus[e] (kg N ha^{-1} $year^{-1}$)	3	−25	4	53	3	−2	137	56	55	2	22	−23	0	−9	19
Total balance[f] (kg N ha^{-1} $year^{-1}$)	28	7	30	70	25	40	165	66	65	16	54	9	28	20	48
NUE[g] (%)		821	96	36	97	103	46	61	62	95	83	611	100	129	83
NUE*[h] (%)		79	72	30	76	62	41	57	58	74	66	75	75	66	66
AE[i] (%)			65	2	66	63	35	42	43	39	63	−57	69	41	59
FUE[j] (%)			71	22	78						52		76		65
AUE[k] (%)						47	37	58	59						

[a]Estimated from standard values, 28 kg ha^{-1} and 9% protein, N% = protein/6.25.
[b]Estimate according to Pihl Karlsson et al. (2012).
[c]Annual decline in N stocks in the topsoil (0.20 m) according to the linear slope of a regression line fitted to bi-annual soil organic nitrogen concentration measurement (1999–2019), multiplied by bulk density (measured in 2009 by Kätterer et al., 2011) and soil depth.
[d]All inputs including N mining.
[e]Inputs (excluding N mining) minus N in harvested biomass.
[f]Inputs (including N mining) minus N in harvested biomass.
[g]Nutrient use efficiency, that is, harvested N over inputs (excluding N mining) in percentage.
[h]Nutrient use efficiency, that is, harvested N over inputs (including N mining) in percentage.
[i]Agronomic efficieny, that is, difference in harvested N in treatment and unfertilized control over inputs (excluding N mining) in percentage.
[j]Fertilizer use efficiency (percentage) accounting for differences in harvest N (h) and N mining (m) between the fertilized treatment (subscript t) and the corresponding unfertilized control treatment (subscript c): $[(h_t–h_c)–(m_t–m_c)]$ divided by annual fertilizer input (80 kg N ha^{-1}). Control treatments were those with corresponding amendments, that is, CaN for treatments AS and CN, Str for Str + N, Peat for Peat+N and SD for SC + N.
[k]Amendment N use efficiency (percentage) was calculated in the same way as FUE but with annual N input from amendments in the denominator. The control treatment here was always the unfertilized control (Unf).

around 4.1, which has led to very low maize yields during recent years.

Yields, relative to those in treatment CaN, strongly responded to an increase in soil pH between values of 4 and 5 (Figure 3). According to the calibrated response function, yields increased from zero at R_0 at pH 4.07 to 50% at pH 4.38 ($R_0 + K$) and to 85% at pH 5 of the yield obtained at soil pH 6.54. An increase in pH from 6.54 in treatment CaN to 7.26 in treatment CN further stimulated biomass production by 2% according to the response function. In comparison, yield measurements average over the period 2000–2019 were 3% higher in treatment CN than in treatment CaN (Table 1). This response function was used to estimate R_{pH} for all treatments for the average soil pH during the targeted period (Table 1). Predicted yield responses to soil pH were similar across 11 treatments and deviated by a maximum of 3% from unity (R_{pH}-values between 0.97 and 1.03), but for three of the treatments (Peat, SS and AS) with severe acidification (soil pH: 5.62, 4.90 and 4.18, respectively), corresponding yield reductions were higher: 6, 18 and 70% (R_{pH}-values 0.94, 0.82 and 0.30).

3.3 | Nitrogen balances, N efficiencies and N mining

Input–output estimates of nitrogen are essential for improving nitrogen management in agroecosystems. The nitrogen balances for the treatments disclosed several interesting insights about N cycling (Table 2). The N surplus was naturally most negative in the unfertilized treatment without amendments (Unf) and in the unfertilized treatment receiving sawdust with low N concentration (SD). The surplus was highly positive in the acidic treatment AS, in the farmyard manure treatments (FYM and FYM + P), and especially in the SS treatment. Negative N surplus values were closely related to high NUE, which was close to 100% in the N fertilized treatments without amendments, or even above 100% in the control (Unf) and in treatments without N fertilizer but receiving amendments with low to moderate N content (Str, GM and Peat). The NUE was lowest in the acidic treatment AS, the farmyard manure treatments (FYM and FYM + P) and the SS treatment. The high values for NUE, especially in the low-N treatments, were due to decreases in SON stocks. Surprisingly, all treatments lost SON during 1999–2019, between 10 and 42 kg N ha^{-1} year^{-1} on average, and SOC was lost in 11 out of 15 treatments during the same period. Thus, net N mineralization of SON (N mining) was a major N source for the maize, especially in the low-N treatments. Primarily in the treatments with organic amendments, the positive trend over time in SOC and SON shifted from positive to negative around the year 2000 with the onset of maize cultivation (Figures 1 and 7). Maize is uncommon in central Sweden, and in our experiment, it has been sown quite late in spring. The Ultuna experiment is not intended for optimizing maize productivity, and crop yields were generally low, reaching only around 8 Mg DM ha^{-1} on average in the best treatment (Table 1). The potential length of the growing season for maize in the area is about 140 days and has not been fully utilized. Indeed, the mean growth period for maize at our site was only 95 ± 10 days, which is also 25 days less than the average growth period of the C3 crops grown during the 1956–1999 period. Furthermore, the root/shoot ratio of the C3 crops grown at this site (mostly small-grain cereals) is about 0.2 under Scandinavian conditions (Palosuo et al., 2016), whereas typical root/shoot ratios for maize for such a short growth period are usually lower and around 0.1 or less (Amos & Walters, 2006; Hirte et al., 2018; Xu et al., 2020). Consequently, C input through maize roots was probably lower than root inputs during the years before 2000, which partly may explain the decline in SOC and SON during recent decades.

The N mining was lowest in the farmyard treatments (FYM and FYM + P) and highest in treatment GM receiving green manure. A potential interpretation for high N mining in GM could be that priming was stimulated through the input of fresh plant biomass. This is supported by recent findings from incubations of soils from a long-term experiment, where priming in a manure-amended soil was lower than in a soil receiving only mineral N or NPK fertilizers (Wu et al., 2023). The increase in N mining was associated with increased ratios of dissolved organic C and N. Although the soluble C fraction was similar in the added green and farmyard manure in our experiment, the former decomposed more than three times as fast as the latter in a 3-day incubation study (Peltre et al., 2012) and had also lower N concentrations (Table 1).

The frequently used NUE index was well above its global median value (46% according to Zhang et al., 2021), but was not very helpful in our context where NUE exceeded 100% in several treatments. When including N mining as a source of N (NUE*), N use was most efficient (79%) in the unfertilized control (Unf) and lowest in the SS treatment (O). Even several of the N-fertilized treatments (CaN, CN and SD + N) had NUE*-values above 70%. Except for the acidic treatment (AS), the AE was also relatively high (59%–69%) in all N fertilized treatments (CaN, CN, Str + N, Peat+N and SD + N).

FUE was highest (78%) in treatment CN. Since crop uptake was similar (about 80 kg N ha^{-1} in both CaN and CN), the higher FUE in CN compared with CaN was

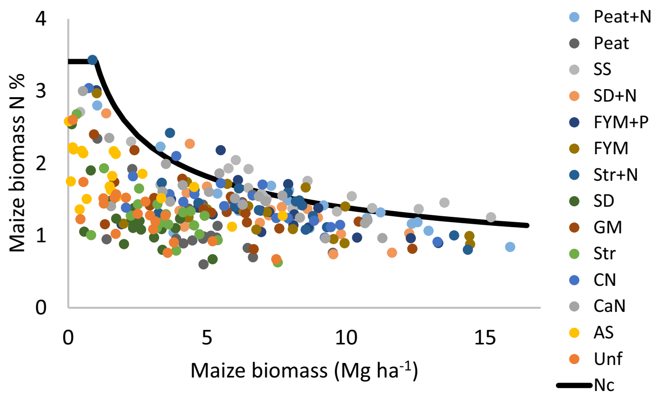

FIGURE 5 Nitrogen concentrations in harvested maize biomass across treatments and years (2000–2019) as a function of dry matter yield (see Table 1 for the description of treatments). The black line represents the critical nitrogen concentration $N_c = 3.41 \cdot DM^{-0.391}$ according to Equation (2) adapted from Herrmann and Taube (2004).

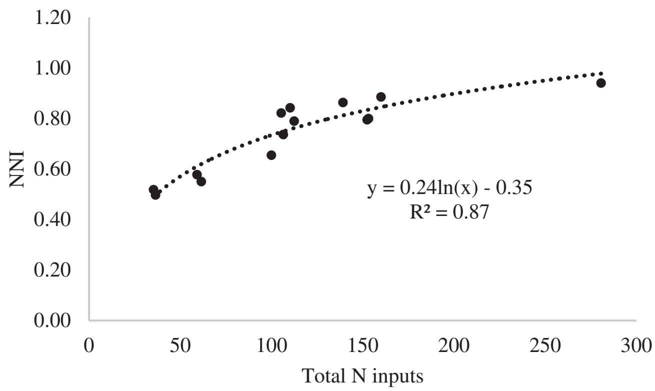

FIGURE 6 Nitrogen nutrition index (NNI) versus total N inputs from seeds, N deposition, fertilizer, amendments and N mining for 14 treatments in the Ultuna frame trial (i.e., bare fallow excluded).

mainly governed by lower N mining in CN, which indicates that the higher soil pH in CN did rather slow down than accelerate the turnover of soil organic matter. This is in contrast to Leifeld et al. (2013) who observed decreasing mean residence times of SOC with increasing soil pH along a natural acidity gradient in alpine grasslands.

The efficiency of N use from N-rich amendments (AUE) was generally lower than FUE. It varied between 37% in SS and 59% in FYM + P. Efficiencies of N use from treatments receiving low-N amendments are less relevant to consider since these are representing legacy effects, where the treatments have resulted in N immobilization rather than N mineralization and the built-up of soil N stocks.

3.4 | Nitrogen nutrition index

Nitrogen concentrations in harvested maize biomass varied greatly between years and treatments (Figure 5). The calculated *NNI* (Equation 3) averaged over the period 2000–2019 per treatment is presented in Table 1. It is not surprising that the unfertilized control treatment (Unf) was severely N-limited (*NNI* = 0.52) and that the SS treatment with excessive N input was the least N-limited treatment (*NNI* = 0.94). The unfertilized treatments (Str, Peat and SD) that received N-poor organic inputs, such as straw, peat and sawdust, were also severely N-limited (*NNI* from 0.50 to 0.58). The treatment with green manure addition (GM) was moderately N limited (*NNI* = 0.74). The relatively low *NNI* (0.65) in the acidified AS treatment may indicate that free aluminium in the soil solution severely affected root functioning. In the other treatments receiving mineral fertilizer or farmyard manure, *NNI* varied between 0.79 and 0.89, indicating a moderate degree of N limitation.

In this study, the evaluation of efficiency indexes did not support our hypothesis that nitrogen cycling was more efficient in high-SOC treatments. Indeed, NUE*, FUE and AUE correlated negatively with SOC. Correlation coefficients were − 0.33, −0.84 and − 0.35, respectively. This negative correlation may be related to more intense N cycling at high SOC, which may result in increased N leaching and gaseous N losses, especially during autumn (Guenet et al., 2021; Powlson et al., 1989). However, *NNI* was closely related to total N inputs (Figure 6; Table 2). This relationship was well described by the logarithmic dose/response relationship ($R^2 = 0.87$), which implies that the impact of additional N input on *NNI* decreased with input rates. However, it has to be considered that this response includes both mineral fertilizers and organic amendments, where the N efficiency of organic amendments (AUE) was generally lower than that of mineral fertilizers (FUE).

3.5 | Yield determinants

We used the BD, and the estimated R_{pH} and *NNI* values (Table 1) for the 14 treatments in a multiple linear regression analysis (Figure 7). The model shows that nitrogen status in maize was the major determinant of maize yield, where *NNI* explained 79% of the variation in crop yield among treatments; R_{pH} and BD explained 12% and 5%, respectively. The impact of all three variables on yield was significant ($p < 0.01$), and the multiple regression model explained 95% of the variation in yields. The model intercept was not significantly different from zero. This shows that it was possible to separate the positive

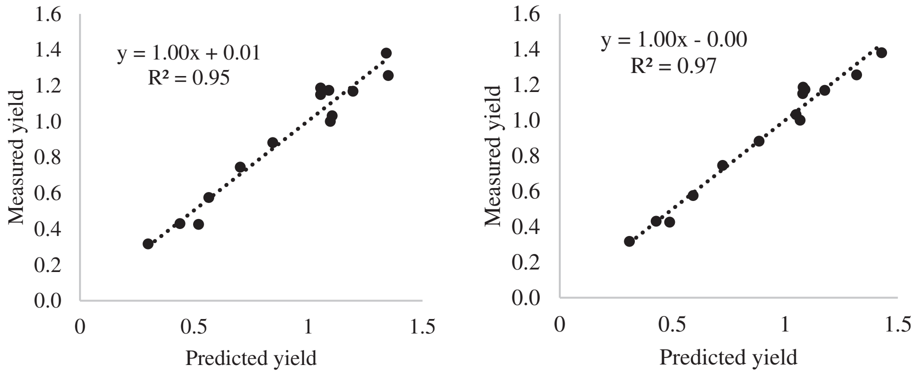

FIGURE 7 Measured versus predicted average maize yields normalized for the standard treatment C in 14 of the treatments in the Ultuna frame trial during the period 2000–2019 according to two models. Left panel: Y = 0.0714 + 1.653·*NNI* + 0.775·R_{pH} − 0.892·BD; right panel: −1.222 + 0.131·SOC + 1.841·*NNI* + 0.562· R_{pH} (see the text for details).

impact of SOC on maize productivity into an effect related to N supply or uptake efficiency and a physical effect related to BD. This model describing maize yield (*Y*) normalized for the standard treatment CaN (i.e., yields in CaN are equal to 1) is:

$$Y = 0.0714 + 1.653 \cdot NNI + 0.775 \cdot R_{pH} - 0.892 \cdot \mathrm{BD}. \quad (4)$$

This implies that a decrease from 1.4 to 1.0 Mg m^{-3} (the range of BD values in the experimental treatments) would increase plant productivity by 29% under non-limiting N conditions at reference soil pH (6.54). At sub-optimal N supply and soil pH, the predicted relative impact of BD increases, for example, to a 35% productivity increase at a simultaneous 10% decrease in *NNI* and R_{pH} (corresponding to pH 5.3).

It is well known that soil organic matter correlates negatively with the BD of soil (Jeffrey, 1970). Therefore, SOC, a common proxy for soil organic matter, is included as a predicting variable for hydraulic soil properties in many pedotransfer functions (Rawls et al., 2003). In our experiment, the negative slope of the regression line BD versus SOC measured in 2009 was 0.122 ($R^2 = 0.67$) according to Kätterer et al. (2011), which means that an increase in SOC by one unit percentage will lead to a decrease in BD of 0.122 Mg m^{-3}. This slope is almost identical to that derived from a database for agricultural soils across Sweden (Kätterer et al., 2006), which indicates that our results are representative, a least for Swedish soils although the intercept of this functional relationship varies between soil types (Kätterer et al., 2011). Substitution of measured BD (which is measured much less frequently than SOC) in equation 4 with its estimate derived from SOC (BD_{est} = 1.469–0.122·SOC) resulted in a similar model fit, explaining 96% of the variance (not shown). Substitution of measured BD with measured SOC in the multiple regression model together with *NNI* and R_{pH} as independent variables resulted in the following model that explained 97% of the variation in Y (Figure 7):

$$Y = -1.222 + 0.131 \cdot \mathrm{SOC} + 1.841 \cdot NNI + 0.562 \cdot R_{pH}. \quad (5)$$

The impact of the three variables on yield was highly significant ($p \leq 0.0005$), and partial R^2-values for *NNI*, R_{pH} and SOC were 79%, 11% and 7%, respectively. Interactions between these three variables were not significant. This implies that crop yields are predicted to increase by 0.131 units, or 10% when SOC increases from 1% to 2%, for each unit increase in SOC percentage due to changes in soil physical properties (i.e., when both *NNI* and $R_{pH} = 1$). When excluding the treatment with an extremely low pH value (treatment AS) from the analysis, the slope of SOC in the regression model slightly increased from about 10% to 13% yield increase per unit increase in SOC. Yields (relative to the treatment CaN) in the high-N treatments in our experiment increased by 16% for each unit change in SOC (Figure 4). Thus, a major part, of a least two thirds (10/16 = 63%), of the SOC effect on crop yield was likely due to processes associated with changes in soil physical properties, rather than nutrient cycling.

3.6 | Effects of SOC on PAWC

Soil water retention characteristics were measured in 1997 in the topsoil (0–20 cm) in nine treatments (BF, Unf, CaN, Str, GM, SD, FYM, Peat and SS; Kirchmann & Gerzabek, 1999). When regressing water content at different soil water tensions on SOC concentration, the slopes of the regressions generally declined with soil water tension in their study. Thus, water content under dry conditions was less affected by SOC than under wetter conditions, which is in accordance with many previous studies (Hudson, 1994). At the highest tension measured by Kirchmann and Gerzabek (1999), pF 3.5, corresponding to the pressure of a 30 m water column, the slope of the regression was insignificant. Assuming that water content at wilting point (pF 4.2) was not responsive to SOC, we used the measurement of wilting point from a

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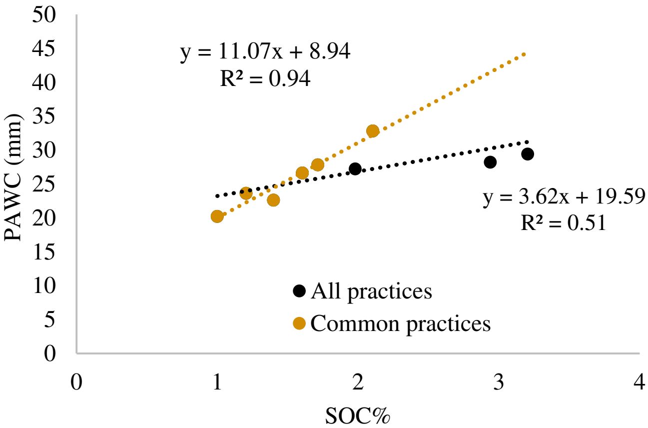

FIGURE 8 Response of plant available water capacity (PAWC) in the topsoil (0–20 cm) to SOC in nine selected treatments, calculated based on data from Kirchmann and Gerzabek (1999). The dataset was split into two categories: only common (BF, Unf, CaN, Str, GM and FYM, in orange) and all agricultural practices including less common ones (Peat, SD and SS, in black). The trend lines concern the former group or the whole dataset (both groups).

soil profile in 1969 adjacent to the experimental plots (17.2%; Wiklert et al., 1983) to calculate plant available water capacity (PAWC), that is, the difference in volumetric soil water content between field capacity (pF 2) and wilting point (pF 4.2). With this assumption, PAWC in the upper 20 cm layer varied between 20.2 mm in the bare fallow and 32.8 mm in the farmyard manure treatment (Figure 8). For the six treatments BF, Unf, CaN, Str, GM and FYM, reflecting common agricultural practices, PAWC increased by 11.1 mm per unit percentage increase of SOC ($R^2 = 0.94$). This relationship was less clear for the treatments SD, Peat and SS that received sawdust, peat and SS, which are rather uncommon amendments in agriculture, and were so probably also during its historic land use. When including those in the regression, PAWC increased only by 3.6 mm per unit SOC%, and the coefficient of determination decreased to $R^2 = 0.51$ (Figure 8). Relative to SOC concentration, these three treatments seemed to have affected soil pore space and PAWC less than the others. This may relate to the findings by Gerzabek et al. (2001), who found that the extra SOC accumulating in these treatments in samples from 1997 was preferentially recovered in silt and sand fractions rather than in the clay fraction. Another fractionation study on samples taken in 1998 also showed that SOC in the clay-sized fraction was most enriched in ^{13}C and ^{15}N, indicating the most intense turnover of soil organic matter in the farmyard manure treatment and least in the peat treatment (Kirchmann et al., 2004). Treatment differences in SOC quality were also apparent according to a size and density fractionation study on samples from 2004 (Magid et al., 2010). According to their study, a much lower proportion (around 40%) of total SOC was recovered in the smallest fraction (<0.05 mm) with the highest density (>1.85 Mg m^{-3}) in the sawdust and SS treatments compared with, for example, the bare fallow and unfertilized control treatments (where this fraction contributed by almost 70% to total SOC). The sawdust and peat had also the highest cellulose-, lignin- and cutin-like fractions among amendments according to the Van Soest fractionation scheme (Peltre et al., 2012). Furthermore, the relatively high C/N ratios in peat and sawdust treatments (Table 1) also indicate that these materials may decompose more slowly than other organic inputs and therefore accumulate in silt and sand fractions rather than in mineral-associated organic matter in clay size fractions. Nevertheless, the organic matter in the SS treatment had a relatively low C/N ratio (9.6). The slow decomposition of sludge was probably masked by its low C/N ratio (8.0). The high content of iron and aluminium in the sludge, which had been added to wastewater in the treatment plant for precipitating phosphorus, and high concentrations of heavy metals during the early decades of the experiments, may also have decreased its accessibility for decomposers (Börjesson et al., 2014). The low soil pH in the sludge treatment and high concentrations of free aluminium and iron may also have affected decomposition (Xiang et al., 2023) as well as soil structure (Šimanský & Jonczak, 2020).

However, the relatively low impact of SOC on PAWC in the treatments with high SOC does not reflect the overall effect of the peat and sludge treatments on water storage because our analysis was limited to the upper 20 cm of the soil profile. According to Menichetti et al. (2015), these two treatments significantly affected SOC, also in the upper subsoil, to a depth of 35 cm. Since topsoil layer thickness increases proportionally to changes in BD, which in turn is closely related to SOC, topsoil layer thickness and SOC are closely correlated (Meurer, Chenu, et al., 2020). This was clearly shown in samples taken in 2009 in our experiment based on both plot elevation measurements and mass balances (Kätterer et al., 2011). Therefore, when considering only the topsoil, the effects of SOC on PAWC in these treatments will be underestimated.

Our estimated increase in topsoil PAWC by 11.1 mm for each unit increase in SOC% for the most common agricultural practices is relatively high compared with several previous studies (Bagnall et al., 2022; Lal, 2013, 2020) but within the range reported by others (Hudson, 1994). We see three major reasons for the relatively strong response in our study. Firstly, the clay content (36.5%) is comparatively high, and thus, aggregation may respond stronger to SOC in our study than in studies based on more coarse-textured soils. Secondly, all management in the Ultuna small-plot frame trial is done by hand, and the soil is not compacted by vehicles, which likely resulted in a stronger response in structure to changes in SOC compared to large plots or on-farm experiments using full-scale machinery. Thirdly, the impact of SOC and topsoil layer thickness has not been considered in previous reviews and meta-analyses. The latter argument has implications for PAWC in the field. According to Kätterer et al. (2011), topsoil layer thickness increased by 2.3 cm for each unit of SOC% increase, which means that the same mass of soil is distributed within a greater soil volume. Thus, the whole volume of plant available water of this extra 2.3 cm layer has to be added to the effect of 11.1 mm. For the farmyard manure treatment, for example, this corresponds to an additional water storage capacity of 3.8 mm. Consequently, the total increase in PAWC was almost 15 mm in our experiment per unit of SOC% increase. Particularly during dry spells, this extra storage of water may become decisive for crop productivity (Liu et al., 2023).

4 | CONCLUSIONS

Our analysis showed that maize yield in the treatments that are not severely limited by nitrogen supply (i.e., treatments receiving at least 80 kg N ha^{-1} $year^{-1}$ as inorganic fertilizer or organic amendments) or soil acidity (pH <5) increased by 16% for each percentage unit increase in SOC. Three variables were identified as yield-determining factors, that is, soil pH, the N status of the crop and BD (as a proxy for soil physical properties). These variables together explained 95% of the variation in maize yields between treatments. According to the resulting multiple regression model, yield responses were sensitive to BD. Estimated potential yields that were neither limited by acidity nor nitrogen, according to this model, increased by about 10% for each percentage unit increase in SOC. Since the model accounted for the biochemical limitations (nitrogen and soil pH), this yield response to SOC should represent the response to changes in soil structure associated with the changes in SOC. We conclude that a major part, likely as much as two thirds of yield responses to SOC change, could be ascribed to associated changes in soil physical properties. Since the use efficiency of nitrogen was not noticeably affected by the level of SOC, the extra storage capacity of plant available water associated with SOC (i.e., which increased by almost 15 mm in the topsoil per unit of SOC% increase) was most likely the main driver for the observed yield responses. It should, however, be considered that the yield responses to SOC may not be directly transferable in a quantitative way from the Ultuna trial to farm-scale conditions. In farmers' fields, soils are frequently compacted by agricultural machinery, which impacts negatively on soil porosity and water storage capacity. Nevertheless, the positive effect of SOC on water storage capacity suggests that measures for increasing SOC in cropland are most likely an effective adaptation strategy for maintaining crop productivity under future climatic conditions with more frequent dry spells, even in relatively humid climates such as in Sweden.

AUTHOR CONTRIBUTIONS

Thomas Kätterer: Conceptualization; methodology; software; data curation; investigation; validation; formal analysis; funding acquisition; visualization; project administration; writing – original draft; resources. **Martin A. Bolinder:** Writing – review and editing; conceptualization.

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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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