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Do soil organic carbon levels affect potential yields and nitrogen use efficiency? An analysis of winter wheat and spring barley field trials

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ABSTRACT

Soil organic carbon (SOC) is broadly recognised as an important parameter affecting soil quality, and can therefore contribute to improving a number of soil properties that influence crop yield. Previous research generally indicates that soil organic carbon has positive effects on crop yields, but in many studies it is difficult to separate the effect of nutrients from the effect of SOC in itself. The aim of this study was to analyze whether the SOC content, in itself, has a significant effect on potential yields of commonly grown cereals across a wider range of soil types in Denmark. The study draws on historical data sets from the Danish national field trials consisting of 560 winter wheat (*Triticum aestivum* L.) trials and 309 spring barley (*Hordeum vulgare* L.) trials conducted over the past 20 and 17 years, respectively. We hypothesised that for these two crops, the potential grain yield, the yield with no fertiliser N application and the N use efficiency would be positively affected by SOC level. A statistical model was developed to explore relationships between SOC and potential yield, yields at zero N application and N use efficiency (NUE). The model included a variety of variables and aimed to elucidate the sole effect of SOC by controlling for potential confounding variables. No significant effect of SOC on potential winter wheat was found, whilst for spring barley, only for the course sandy loam soil type was a borderline significantly positive effect of SOC on potential yields found. The relationship between unfertilized plot yields and SOC was positive for winter wheat, although not significant, whilst for spring barley a significant positive effect of SOC was found only for the coarse sandy soil type, and a borderline significant positive effect of SOC was found for the coarse sandy loam soil type. A significant negative relationship was found between SOC and NUE for both winter wheat and spring barley. Based on the large dataset analyzed, we cautiously challenge the importance of SOC in contributing to crop productivity in contexts with similar soils and climate, and we speculate that in situations where nutrient limitation does not occur, SOC levels above 1% may be sufficient to sustain yields. In light of the findings presented in this study, further work should be conducted which can further elucidate the effect of SOC on yields.

1. Introduction

Soil organic matter (SOM) is broadly recognised as an important parameter affecting soil quality (Diacono and Montemurro, 2010; Johnston et al., 2009). Therefore, land use and management systems which maintain or enhance levels of SOM are considered pivotal in ensuring agricultural sustainability and productivity (Lal, 2006). SOM is furthermore of global environmental importance primarily due to the role that soil organic carbon[1] (SOC) plays in carbon sequestration (Morgan et al., 2010).

Crop yields are influenced by a range of factors including solar radiation, water and nutrient availability and pest and weed pressure (Evans, 1993). Soil organic matter influences soil biological, physical and chemical properties, therefore from an agronomic perspective, SOM is considered important as it can contribute in a variety of ways to improving some of the factors influencing

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[1] We use the terms SOM and SOC interchangeably. In our analysis, we refer primarily to SOC, whilst in Sections 1 and 4 we use both terms according to how cited references have used the term.

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crop yield. SOM has been associated with: better plant nutrition, particularly as a potential source of nutrients, improved soil structure, improved water holding capacity and soil buffering capacity (Johnston et al., 2009; Loveland and Webb, 2003). SOM levels are thus intimately linked to soil parameters central to an economically and environmentally sustainable agriculture (Christensen and Johnston, 1997).

A number of studies have investigated the effect of SOM on yields. Lal, 2006 reviewed the effect of SOC on crop yields, focussing primarily on sub-tropical and tropical countries. For wheat grown in the tropics and sub-tropics, the review found that an increase in SOC levels increases wheat yields, particularly in instances where SOC is depleted (Lal, 2006). In a later review of studies reporting the effect of SOC on crop productivity, Lal, 2010 further demonstrates a positive effect of increasing SOC content on crop yields for a variety of crops and locations (including Russia, China and Argentina). The author, however, stressed that crops' agronomic response to SOC concentration depends on numerous factors such as the active or mineralizable C fraction and managerial inputs (especially of nutrients and water) (Lal, 2010).

The organic manuring experiment in Woburn (Johnston et al., 2009) shows that yields for a rotation of potatoes, winter wheat, sugar beet and spring barley were always larger on soils holding more organic matter, despite equal levels of nitrogen (N) application. Similarly, cultivation of spring barley (Hoosfield continuous Barley experiment) resulted in higher yields on fields with higher levels of SOM for three of four cultivars reported (Christensen and Johnston, 1997; Johnston et al., 2009). The evidence from these experiments is quite variable and suffers from the fact that they are obtained on one location and can therefore be difficult to generalize. In China, soil organic matter has been found to correlate with cereal crop productivity and yield stability across several provinces (Pan et al., 2009), although their analysis did not account for other variables that might explain yield. Diaz-Zorita et al., 1999 and Alvarez et al., 2002 investigated the relationship between wheat yields and SOM in the semi-arid Argentine Pampas. Diaz-Zorita et al., 1999 showed that wheat grain yields (ranging from 1711 to 2233 kg ha^{-1}) were significantly correlated with soil water retention and total organic carbon (ranging from 10.6 to 15.6 g kg^{-1}) in years when moisture availability was the primary limitation, whilst in years with sufficient rain, wheat yields were correlated with total N and available P contents in the soil. Alvarez et al., 2002 found that SOM content (averaging 45 Mg ha^{-1} for 0–20 cm in the experiment) was the most important explanatory variable of wheat yields (ranging from 1000 to 5000 kg ha^{-1}); however, other variables which also correlated positively to yield included rainfall and potential mineralizable N. In these experiments, higher SOC content would also be associated with better nutritional status of the soil and therefore the improved yields may be an effect of crop nutrient supply rather than an effect of the SOM itself. Loveland and Webb, 2003 conclude there is some evidence that SOC reduction leads to a reduction in yield potential, although these reductions are small, whilst Körschens et al. (2013, 1998),) demonstrate marginal positive effects of SOM on potential yields.

The objective of this study is to analyze the effect of SOC content on potential yields of winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.) across a wide range of soil types. We test the hypothesis that potential grain yield, yield with no fertiliser N application and the N use efficiency will be positively affected by SOC level. In this study we define potential yields as the yield of a crop cultivar when grown under non-limiting nutrient availability and normal conditions of water availability and disease control. This means that it is only potential in terms of nutrient availability (Evans, 1993). Nitrogen use efficiency (NUE) is defined in this study as a measure of the increase in kg grain N content per kg N applied (Ladha et al., 2005).

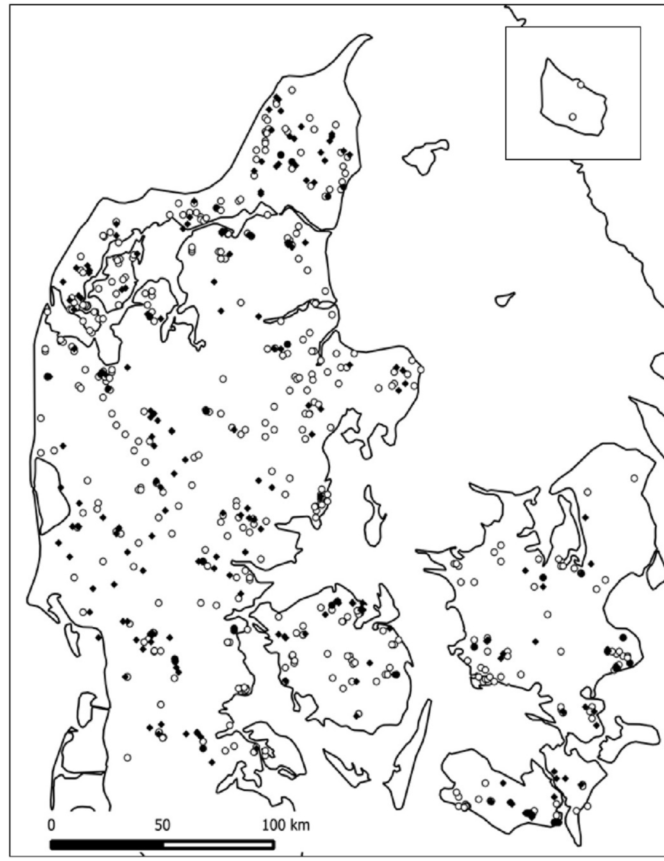

Fig. 1. Overview of the location of experimental sites in Denmark for the winter wheat trials (open circles), $n = 549$ and spring barley trials (diamonds), $n = 286$.

2. Materials and methods

2.1. Experimental data used for the analysis

Experimental data included in this analysis are from the national field trials conducted in Denmark between 1989 and 2009 by the local branches of the Danish Agricultural Advisory Service. Datasets were extracted from a database of the trials maintained by the Danish Knowledge Centre for Agriculture (Nordic Field Trial System[2]). The primary aim of the field trials included in the analysis was to quantify crop response to N fertilizer applications, relating both to fertilizer type and to determination of the economically optimal N application rate. Yield data were for winter wheat for the period 1989–2009 from 560 farmer field sites in total, and for spring barley for the period 1992–2009 from 309 sites in total. The trials were conducted at different sites each year, geographically covering all climatic regions and soil types in Denmark. The data set thus widely covers Danish arable land. Fig. 1 provides an overview of the location of sites for winter wheat and spring barley in Denmark. Note that we lacked co-ordinates for some sites, therefore the number of sites in Fig. 1 is lower.

2.2. Experimental design and treatments

The winter wheat and spring barley experiments were conducted at the respective field sites using a block design with 5 replicates for each treatment with plot sizes ranging from 25 to 35 m^2. For winter wheat, treatments were different mineral

[2] Accessible online at https://nfts.dlbr.dk/ (Version 1.0.0.16796).

Table 1
Soil types represented in the data based on the Danish soil classification system, a description of each soil type and the number of experimental sites for each soil type for winter wheat and spring barley.

Code	Texture definition	Percentage by weight				Winter wheat (n)	Spring barley (n)
		Clay (<2 μm)	Silt (2–20 μm)	Fine sand (20–200 μm)	Total sand (20–2000 μm)		
JB1	Coarse sandy soil	0–5	0–20	0–50	75–100	26	39
JB2	Fine sandy soil	0–5	0–20	50–100	75–100	26	19
JB3	Coarse sandy clay soil	5–10	0–25	0–40	65–95	37	40
JB4	Fine sandy clay soil	5–10	0–25	40–95	65–95	92	76
JB5	Coarse sandy loam	10–15	0–30	0–40	55–90	54	19
JB6	Fine sandy clay loam	10–15	0–30	40–90	55–90	157	57
JB7	Clay loam	15–25	0–35		40–85	156	57
JB8	Clay soil	25–45	0–45		10–75	12	2

fertilizer N application rates ranging between 0 and 250 kg N ha^{-1} for all experiments. The majority of the experiments received six different N rates from 0 to 250 kg N ha^{-1} (0, 50, 100, 150, 200 and 250 kg N ha^{-1}), whilst some experiments received only four N rates. The wheat crop was sown at the end of September or early October each year. Mineral fertilizer N was applied in two doses, with 50 kg ha^{-1} in mid-March whilst the remainder was applied at end of April. For spring barley, six different N rates were applied ranging from 0 to 200 kg N ha^{-1} (0, 40, 80, 120, 160 and 200 kg N ha^{-1}). The largest rates were high enough to attain maximum yields at almost all sites and the sites where it was not attained were removed from the analysis (see Section 2.3). The barley crop was sown in late March or April each year. The N treatment was applied in one dose at the time of sowing.

The experiments were undertaken at private farms across Denmark using conventional farming practices, i.e. not including organic farming practices. All experiments were located in homogeneous, well-managed fields following farmer's typical practices of the surrounding fields. Tillage practices were all normal ploughing and not minimum tillage.

2.3. Measurements and analysis

Grain yield data was recorded using an experimental combine harvester, from at least half of each plot. Grain material was ground and total N was determined using the Dumas method until the year 2000, thereafter by near infrared spectroscopy (NIR), continuously calibrated with the Dumas method for 10–15% of the samples. Grain yield was expressed as weight (at 85% dry matter) per area.

Sixteen core soil samples were taken randomly from the depth interval 0.00–0.25 m at each trial area and mixed to form a composite sample. Determination of soil organic carbon was conducted according to the ter Meulen method (ter Meulen, 1924) based on loss on ignition at 550 °C in a LECO IR-12 furnace. For samples with free carbonate the organic carbon content was adjusted for carbonate-C determined by addition of 4 M HCl, trapping of CO_2 in barium hydroxide and back titration (Sørensen and Bülow-Olsen, 1994). Soil carbon content was calculated using a conversion factor of 0.58 g C g^{-1} organic matter (Guo and Gifford, 2002). Soil texture was determined using the hydrometer method. Soils were classified according to the Danish soil classification system, described in Table 1 with an overview of soil types represented in the winter wheat and spring barley experiments, respectively. Analyzes were conducted at the following laboratories: the central laboratory at Foulum, Denmark (1992–2001), at Steins (Eurofins) (2002–2007) and at AgroLab Denmark since 2008.

For each site, a number of variables were recorded and included in the analysis: altitude (ALTITUDE), crop variety (VARIETY), year of observation (YEAR), and amount of total N applied to fields in organic fertilizer (manure, biosolids, urban organic waste composts etc.) cumulated over the 5 years prior to the trial (ORG_N). For each trial, VARIETY was included as a categorical variable (68 and 55 different varieties were used in the winter wheat and spring barley trials, respectively). The true/false variable ORG_{N0} designated if the field received zero N inputs from organic fertilizer sources in the five years prior to the trial. Finally, a categorical variable was included for the number of times straw had been incorporated within the last 5 years prior to the specific field experiment

Table 2
Mean values and standard deviations for the variables in the statistical analysis of winter wheat and spring barley yield. Note these values are not transformed.

Variable	Abbreviation	Unit	Winter wheat		Spring Barley	
			Mean	St. dev.	Mean	St. dev.
Potential yield	$YIELD_{Pot}$	t ha^{-1}	8.1	1.5	5.9	1.3
Nitrogen use efficiency	NUE		0.45	0.10	0.35	0.09
Yield at zero nitrogen (N) dose	$YIELD_{N0}$	t ha^{-1}	4.3	1.6	3.5	1.2
Soil organic carbon	SOC	%	1.7	0.5	1.8	0.6
Clay	CLAY	%	12.6	5.8	9.9	5.3
Organic N[a]	ORG_N	kg N ha^{-1}	295.3	442.8	125.2	144.2
Mean winter global radiation	$Glorad_W$	MJ m^{-2}	674.0	49.9	678.6	52.9
Mean spring global radiation	$Glorad_{Sp}$	MJ m^{-2}	1258.5	87.3	1263.3	95.0
Mean summer global radiation	$Glorad_{Su}$	MJ m^{-2}	887.4	84.3	883.5	82.8
Mean winter precipitation	$Prec_W$	mm	354.5	110.2	368.0	121.2
Mean spring precipitation	$Prec_{Sp}$	mm	116.3	34.8	118.0	36.9
Mean summer precipitation	$Prec_{Su}$	mm	93.5	49.6	94.6	48.8
Altitude	Altitude	m	27.3	21.2	28.2	19.9
Mean winter temperature	$Temp_W$	°C	3.7	1.2	3.6	1.2
Mean spring temperature	$Temp_{Sp}$	°C	9.9	0.9	10.0	0.9
Mean summer temperature	$Temp_{Su}$	°C	15.8	1.4	15.9	1.4
Irrigation	IRRIG	mm	5.7	23.7	12.0	33.1

[a] Applied in the 5 years prior to the trial.

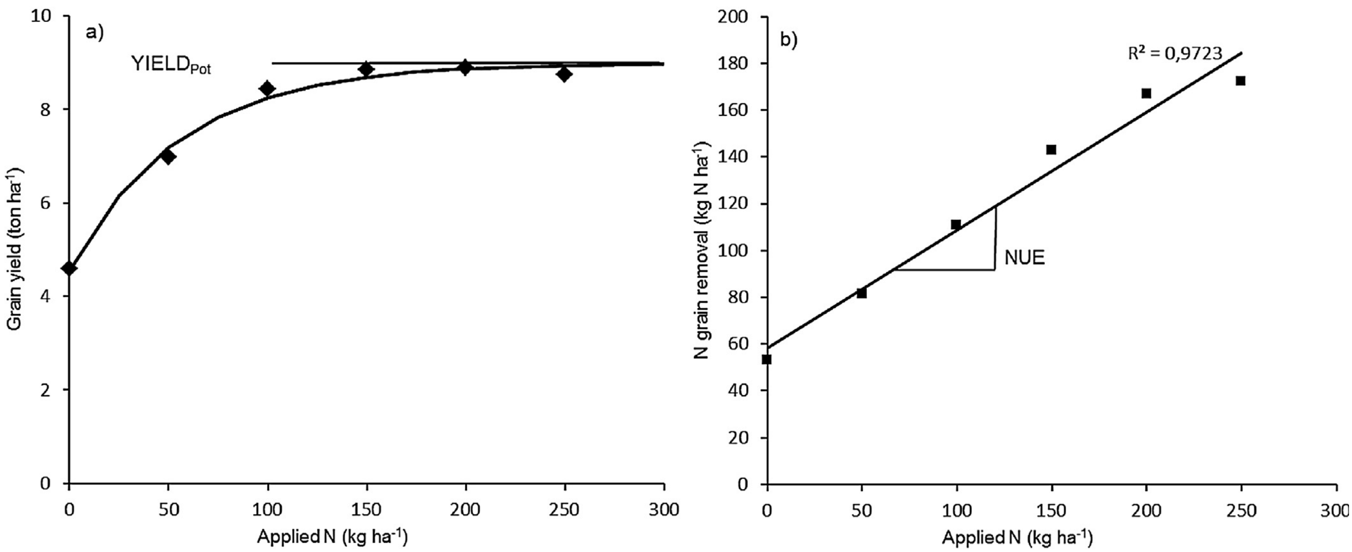

Fig. 2. Examples of data from the field trials. (a) Presents observed (diamonds) and modelled yields (line) for a winter wheat trial for the estimation of potential yield (YIELD$_{Pot}$); (b) presents observed N removal in grain plotted against applied N for the estimation of N use efficiency (NUE).

(STRAW1–5). Table 2 presents mean values and standard deviations for the variables in the statistical analysis.

2.4. Climate data

The climate data was obtained for each location, based on daily interpolated meteorological data for 44 grids of 40 × 40 km covering Denmark (Kristensen et al., 2011). For each location, the data for the grid containing the experimental site was used to calculate: 1) temperature averages (degrees Celsius) during winter time (TEMP$_W$), spring time (TEMP$_{Sp}$), and summer time (TEMP$_{Su}$); 2) global radiation averages, (MJ m^{-2}) for winter time (GLORAD$_W$), spring time (GLORAD$_{Sp}$), and summer time (GLORAD$_{Su}$); and 3), precipitation (mm) for the winter time (PREC$_W$), spring time (PREC$_{Sp}$), and summer time (PREC$_{Su}$). The periods were, for winter: 1 October–31 March, spring: 1 April–15 June, and summer: 16 June–31 July. Finally, site-specific irrigation rates (IRRIG) were included in the analysis. In total 42 sites were irrigated for the wheat trials and 58 for spring barley. Table 2 presents mean values and standard deviations for the variables in the statistical analysis.

2.5. Calculations

Potential yield (YIELD$_{Pot}$) was estimated by fitting a Mitscherlich–Baule response function to the yield data (Frank et al., 1990):

$$Y = \beta_0[1 - \exp - \beta_1(\beta_2 + N)]$$

where Y is wheat average yield in the field replicates (kg ha^{-1}), N is N applied (kg N ha^{-1}). β_0 represents an asymptotic yield level plateau (the potential yield), β_1 and β_2 are parameters. An example of data from a field trial is presented in Fig. 2a. If the estimated potential yield is much higher than the yield attained at the highest N application, this indicates that either the largest application is too low to obtain the potential yield or it is so high that nitrogen inhibition occurs. In either case, the estimate of the potential yield will be unreliable. For this reason, the estimated potential yield was considered too uncertain and was excluded from the statistical analysis if it differed by more than 500 kg ha^{-1} from the yield observed at the highest N application A total of 68 estimates was removed in this way from the dataset for winter wheat and 49 for spring barley. An analysis of the effect of SOC on the actual yield without N application (YIELD$_{N0}$) was also conducted.

Nitrogen use efficiency (NUE) is defined in this study as a measure of kg grain N uptake per kg N applied (Ladha et al., 2005). NUE was estimated as the slope of a linear regression of the average crop grain N uptake in the field replicates against N application, as demonstrated in Fig. 2b. At a few locations, the response in N uptake was not linear at high N application rates. If the R^2 value of a line fitted to the data points below 150 kg N ha^{-1} was higher than a line fitted to all data points, then the slope of the line below 150 kg N ha^{-1} was used in the data analysis instead. If the R^2 values remained below 0.97 the estimate of NUE was considered too low and removed from the dataset. In this way, 36 NUE estimates were removed for the winter wheat and 32 for the spring barley. Slopes from regressions with an R^2 value below 0.97 were excluded from the analysis.

There were a few locations with very high organic matter contents. In order to prevent these observations from influencing analyzes, observations with SOC values greater than 4% were excluded from the analysis (n = 16 and 11 for winter wheat and spring barley, respectively). Furthermore, some values of ORG$_N$ appeared unrealistically large in the wheat data set and therefore observations from locations with ORG$_N$ values greater than 4000 kg N ha^{-1} were also excluded from the analysis (n = 18).

2.6. Statistical analysis

In the current analysis we explored relationships between SOC and three response variables, namely potential yield (YIELD$_{Pot}$),

Table 3
Estimates, 95% confidence intervals (CI) and p-values for the parameters on the transformed covariates in the final model for the transformed potential yield of winter wheat. The numbers are given in transformed units according to the specification in Table 2.

	Estimate	Lower CI	Upper CI	p-value
(Intercept)	0.2485	0.1189	0.3781	0.0002
Soil organic carbon	−0.0992	−0.1989	0.0005	0.0512
Clay	0.4423	0.3441	0.5406	<0.0001
Altitude	−0.1282	−0.2187	−0.0378	0.0056
Mean winter temperature	0.0984	0.0056	0.1913	0.0378
Mean winter global radiation	−0.0858	−0.1508	−0.0207	0.0099
Mean winter precipitation	−0.0906	−0.1595	−0.0216	0.0102

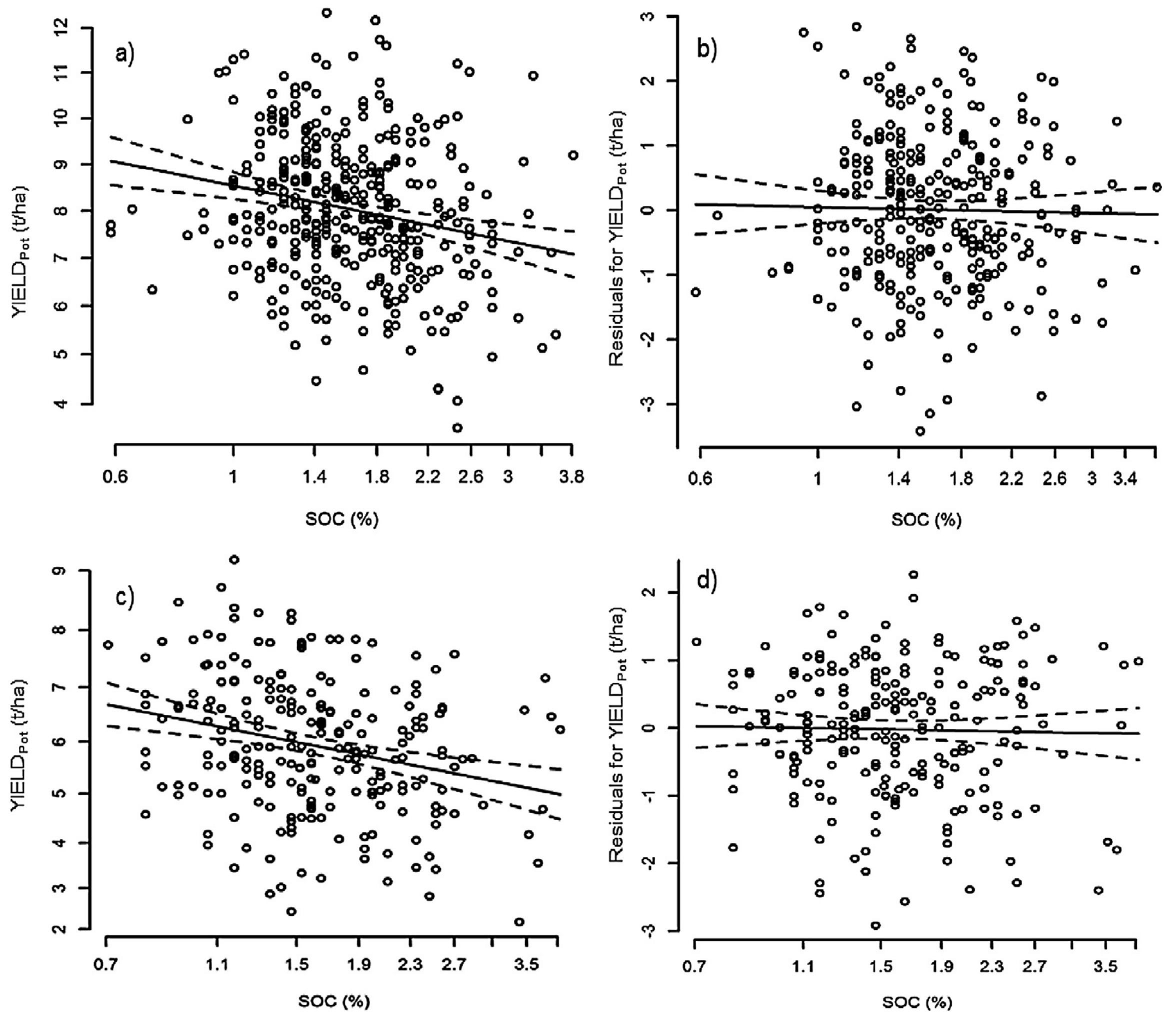

Fig. 3. Potential yield ($YIELD_{POT}$) in winter wheat (a) and spring barley (c) as a function of SOC and the residual plots from the full model (excluding SOC) for winter wheat (b) and spring barley (d) (note the axes are transformed). The solid line is the estimated regression line, whilst the dotted lines demonstrate the 95% confidence interval for the line.

yields at zero N application ($YIELD_{N0}$) and N use efficiency (NUE). The data included in this analysis has been collected from a large number of locations rather than from a single experiment, so factors other than SOC were not controlled. Therefore, there may be variables which are confounded with SOC, i.e., factors that are correlated with SOC, making it difficult or impossible to infer a causal relationship between SOC and the response variable, because the effect might as well be caused by the confounding variable. For example, a confounding variable could be clay content. Increasing clay content would typically be expected to have a positive influence on potential yield. However, many Danish sandy soils with a low clay content hold considerable amounts of organic matter. This can be attributed to intensive dairy production (involving manure application and cultivation of perennial grass crops, and thus increased SOC levels) typically located in regions with sandy soils and soils with a higher content of charred material from previous land-uses (Taghizadeh-Toosi et al., 2014). These two relationships would produce a negative relationship between SOC and potential yield, not because SOC has a negative effect, but because SOC is negatively correlated with clay and clay has a positive effect on potential yields (due to deeper root development and higher capacity for plant available water). The statistical analysis was thus conducted with the aim of removing the effect of as many of the confounding variables as possible.

We created a full statistical model (referred to as full model in the results) that included all main effects, quadratic terms of the continuous covariates, an interaction between soil types (JB1–JB8) and SOC, and random effects of YEAR and VARIETY. Numerical variables included in the model are presented in Table 2. The quadratic terms were included to allow the optimal values of the covariates to be in the middle range, e.g. both too little and too much rain will give a low yield. All continuous variables were non-negative except for a few observations of altitude, and several of the variables had a right-skewed distribution. To improve the statistical modelling, the individual variables were power transformed with positive exponents within the Box-Cox framework (Box and Cox, 1964) in order to achieve best normality. To standardize the scale of the variables, the power transformed variables were subsequently normalized to zero mean and unit standard deviation. The transformations of the variables in Table 2 were conducted using Eq. (1):

$$t(V) = \frac{V^{\mathrm{Exp}} - \mathrm{mean}}{\mathrm{st.dev}} \tag{1}$$

Where $t(V)$ is the transformed variable V where the exponent Exp interval is [0;1]. Since the power transformations, demonstrated by Eq. (1), are monotonically increasing, a positive effect of a variable will remain positive after the transformation. Therefore the sign of a regression coefficient can be interpreted in terms of whether it has a positive or negative effect of yields. The size of the regression

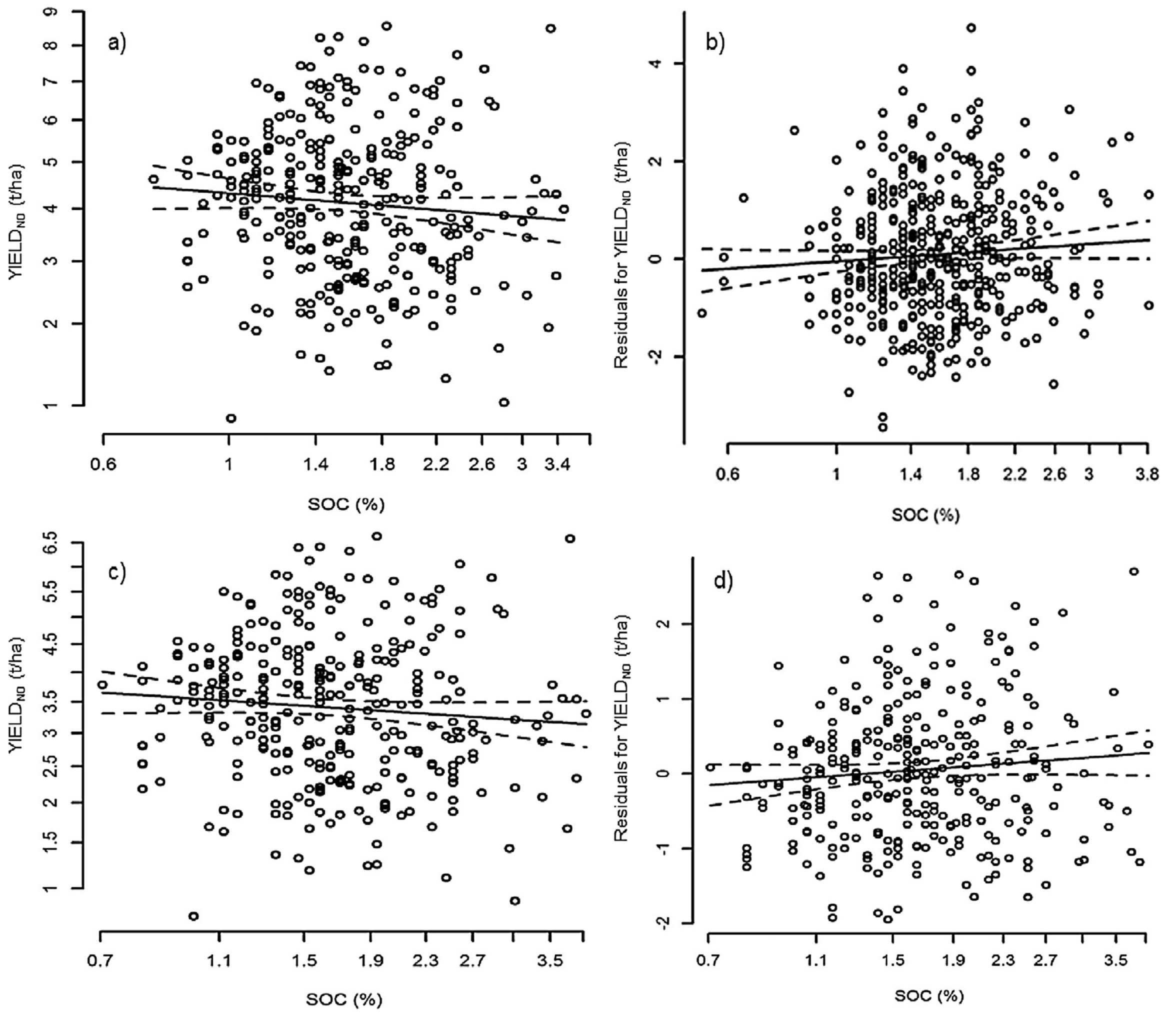

Fig. 4. Yields without fertiliser N application ($YIELD_{N0}$) in winter wheat (a) and spring barley (c), respectively as a function of SOC, and residual plots from the full model (excluding SOC) for winter wheat yields (b) and spring barley yields (d) without fertiliser N application as a function of SOC (note the axes are transformed). The solid line is the estimated regression line, whilst the dotted lines demonstrate the 95% confidence interval.

coefficients are measures in scales of standard deviations, which allow for comparison of the coefficients across the effects.

The full models for each response variable and crop type were validated by quintile plots and residual plots. The residual plots for the full models are presented for each crop type and response variable indicating the residual effect of SOC on the response variable when all other effects are removed. On these plots, the axes were transformed so that SOC and the response variable can be read directly on the graph.

The effect of SOC on the three response variables ($YIELD_{Pot}$, $YIELD_{N0}$, and NUE) was tested in the full model by removing SOC from the model and testing if this decreased the ability of the model to explain the variance in the response variables. The null hypothesis for this test was that there was no effect of SOC on the response variable. If SOC is correlated with other variables, a potential causal effect of SOC could be explained by these variables and we would accept the null hypothesis of no effect of SOC. This approach is conservative in the sense that if an effect is identified, this effect can only be explained by SOC and none of the other variables. However, it is inefficient if we want to show that there is an effect of SOC.

We therefore also analyzed the effect of SOC on the three response variables in a model resulting from backward model reduction of the full model on a 5% significance level with the modification that the main effect of SOC was kept in the model even if it was non-significant. The reduced model is subsequently referred to as the “final model”. Following model reduction, the effect of SOC and the other remaining variables was tested by comparison with a model similar to the final model but without the variable tested for significance. After model reduction, variables were removed that were not significant when SOC was included in the model. If the test showed a significant effect of SOC, there are two possibilities. Either there is a causal effect of SOC, or a confounding variable with a causal effect on the response variable has been removed. Hence, we can not be sure that there is an effect of SOC. However, in the final model, if there is no effect of SOC we can with stronger confidence say there is no evidence of an effect of SOC.

Model selection was done by F-tests when no random effects remained and otherwise by chi-square tests. Coefficients in the final models are reported with 95% confidence intervals and p-values for being non-zero. In case of multiple tests within effects, the p-values for being non-zero are also reported with adjustment using the false discovery rate (Storey, 2002). For models with random effects the parameter p-values are computed by simulations, and may differ slightly from the p-values used in model selection.

All statistical analyzes were performed using the Linear Mixed Effects package (lme4), Goodness of fit (GOF) and standard R packages (www.r-project.org).

Table 4
Final model for the transformed potential yield of spring barley. Estimates, 95% confidence intervals (CI), *p*-values, and adjusted *p*-values for the parameters on the transformed covariates in the model.

	Estimate	CI lower	CI upper	*p*-value	Adjusted *p*-value*
(Intercept)	0.1087	−0.1540	0.3637	0.3970	-
Soil organic carbon:JB1	0.2875	-0.0730	0.6495	0.1130	0.2260
Soil organic carbon:JB2	−0.7010	−1.1933	−0.2117	0.0060	0.0480
Soil organic carbon:JB3	−0.1826	−0.4675	0.0974	0.2064	0.3205
Soil organic carbon:JB4	−0.1183	−0.3313	0.0988	0.2816	0.3218
Soil organic carbon:JB5	0.5629	0.0828	10.528	0.0248	0.0661
Soil organic carbon:JB6	−0.3007	−0.5491	−0.0515	0.0180	0.0661
Soil organic carbon:JB7	−0.0637	−0.3421	0.2192	0.6514	0.6514
Soil organic carbon:JB8	0.5635	−0.3881	15.054	0.2404	0.3205
Clay	0.4730	0.3262	0.6198	0.0000	-
Altitude	−0.1715	−0.2838	−0.0566	0.0026	-
Altitude^2	−0.0706	−0.1411	0.0007	0.0522	-
(Mean spring precipitation)^2	−0.2043	−0.3055	−0.1063	0.0000	-
Irrigation^2	0.0830	0.0050	0.1620	0.0364	-
Year	NA	NA	NA	0.0020	-

[*] Adjusted *p*-value excluded when the value is the same as *p*-value.

3. Results

3.1. The effect of SOC on potential yields in winter wheat and spring barley

Fig. 3a presents a basic plot of potential yield of winter wheat as a function of SOC, demonstrating a negative relationship ($p < 0.0001$). This would seem to indicate that there is a negative effect of SOC on yields, but as explained earlier this seemingly negative effect could be caused by confounding variables that are correlated with SOC. Fig. 3b presents the residual plot of potential yields as a function of SOC, based on the full model including all explanatory variables except SOC. There is no evident significant effect of SOC, given that the residuals are the part of potential yields that cannot be explained by all the other variables included in the full model. In the full statistical model including all the other explanatory variables, the effect of SOC is not significant ($p = 0.52$).

Parameter estimates for the final model for potential yield of wheat, containing all significant explanatory variables and SOC ($R^2 = 0.30$), are presented in Table 3. In the final model, where non-significant variables were removed, a negative influence of SOC was found. This was not significant, but was close to being so ($p = 0.0512$, Table 3). In this model, SOC alone explains almost 5% of the variation ($R^2 = 0.045$).

A negative relationship between SOC and potential yields of spring barley was demonstrated in the plot presented in Fig. 3c ($p < 0.0001$). However, the residual plot based on the full model without SOC of spring barley potential yields as a function of SOC presented in Fig. 3d shows that this relation disappears when spring barley potential yield is explained by all other variables. In the full statistical model including all the other explanatory variables the effect of SOC is not significant ($p = 0.12$).

Parameter estimates for the final reduced model for spring barley ($R^2 = 0.49$) are presented in Table 4. In the final reduced model for potential yield in spring barley, there was a significant interaction between SOC and soil type (JB1–JB8, $p = 0.0005$). A significant negative effect of SOC was found for the soil type JB2 (adjusted $p = 0.0480$), whilst borderline significant effects of SOC were found in the soil types JB6 (negative influence, adjusted $p = 0.0661$) and JB5 (positive influence, adjusted $p = 0.0661$) (Table 4).

3.2. The effect of SOC on yields without fertiliser N application in winter wheat and spring barley

Fig. 4a presents a basic plot of winter wheat yields without fertilizer application ($YIELD_{N0}$) as a function of SOC. The slightly negative relation between $YIELD_{N0}$ in winter wheat and SOC was not

Table 5
Final model for the transformed zero N application yield of winter wheat. Estimates, 95% confidence intervals (CI), *p*-values, and adjusted *p*-values for the parameters on the transformed covariates in the model.

	Estimate	Lower CI	Upper CI	*p*-value	Adjusted *p*-value*
(Intercept)	0.2297	−0.0825	0.5420	0.1489	-
SOC	0.0591	−0.0301	0.1483	0.1936	-
ORG_{N0}[a]	−13.657	−23.353	−0.3961	0.0059	
Organic N applied past 5 years	−0.5481	−10.759	−0.0203	0.0419	0.0419
(Organic N applied past 5 years)^2	0.3615	0.0528	0.6701	0.0218	0.0327
STRAW1[b]	−0.1072	−0.3299	0.1155	0.3447	0.3447
STRAW2	−0.2814	−0.5273	−0.0356	0.0250	0.0499
STRAW3	−0.2885	−0.5933	0.0163	0.0635	0.0847
STRAW4	−0.4334	−0.7118	−0.1550	0.0024	0.0094
CLAY	0.2528	0.1544	0.3511	0.0000	0.0000
CLAY^2	-0.1013	−0.1599	−0.0428	0.0007	0.0007
Altitude	-0.1039	−0.1906	−0.0172	0.0189	-
Mean winter precipitation	−0.2610	−0.3443	−0.1777	0.0000	-
Irrigation	−0.7179	−13.371	−0.0988	0.0232	0.0304
(Irrigation)^2	0.1808	0.0172	0.3445	0.0304	0.0304
(Mean spring global radiation)^2	0.1276	0.0686	0.1865	0.0000	0.0000

[*] Adjusted *p*-value excluded when the value is the same as *p*-value.
[a] A true/false variable designated if the field received zero N inputs from organic fertilizer sources within the past five years.
[b] Variable for number of times straw was incorporated within the 5 years prior to experiment, e.g., straw 1 means straw was incorporated once in the past 5 years, straw 2 means twice in the past 5 years etc.

Table 6
Final model for the transformed yield without fertiliser N application of spring barley. Estimates, 95% confidence intervals (CI), p-values, and adjusted p-values for the parameters on the transformed covariates in the model.

	Estimate	CI lower	CI upper	p-value	Adjusted p-value*
(Intercept)	0.2032	0.0133	0.3899	0.0364	-
Soil organic carbon:JB1	0.5253	0.2168	0.8308	0.0006	0.0054
Soil organic carbon:JB2	0.1324	−0.2608	0.5327	0.5110	0.6570
Soil organic carbon:JB3	−0.0013	−0.2661	0.2640	0.9864	0.9864
Soil organic carbon:JB4	0.1625	−0.0341	0.3545	0.1036	0.2331
Soil organic carbon:JB5	0.5090	0.0269	0.9957	0.0370	0.1110
Soil organic carbon:JB6	−0.1828	−0.4471	0.0821	0.1770	0.3186
Soil organic carbon:JB7	0.1343	−0.1604	0.4287	0.3694	0.5541
Soil organic carbon:JB8	0.2226	-0.8255	12.489	0.6754	0.7598
(Soil organic carbon)^2	−0.1050	−0.1919	−0.0139	0.0254	0.1110
Organic N applied past 5 years	0.2588	0.1533	0.3671	0.0000	-
Altitude	−0.1607	−0.2592	−0.0597	0.0020	-
Clay	0.3856	0.2518	0.5210	0.0000	0.0000
(Clay)^2	−0.1574	−0.2678	−0.0492	0.0044	0.0044
(Mean winter precipitation)^2	0.1414	0.0587	0.2245	0.0008	-
Irrigation^2	−0.0891	−0.1472	−0.0316	0.0022	-
Variety	NA	NA	NA	0.0071	0.0071

* Adjusted p-value excluded when the value is the same as p-value.

significant ($p = 0.39$). The residual plot of SOC as a function of $YIELD_{N0}$ (Fig. 4b), based on the full model excluding SOC, demonstrates a slight positive relation. However, in the full statistical model, the effect of SOC is not significant ($p = 0.28$).

Parameter estimates for the final model of yield of winter wheat ($R^2 = 0.25$) without fertiliser N application ($YIELD_{N0}$) are presented in Table 5. Here, the influence of SOC on $YIELD_{N0}$ was positive but not significant ($p = 0.19$). The R^2 value for marginal SOC,

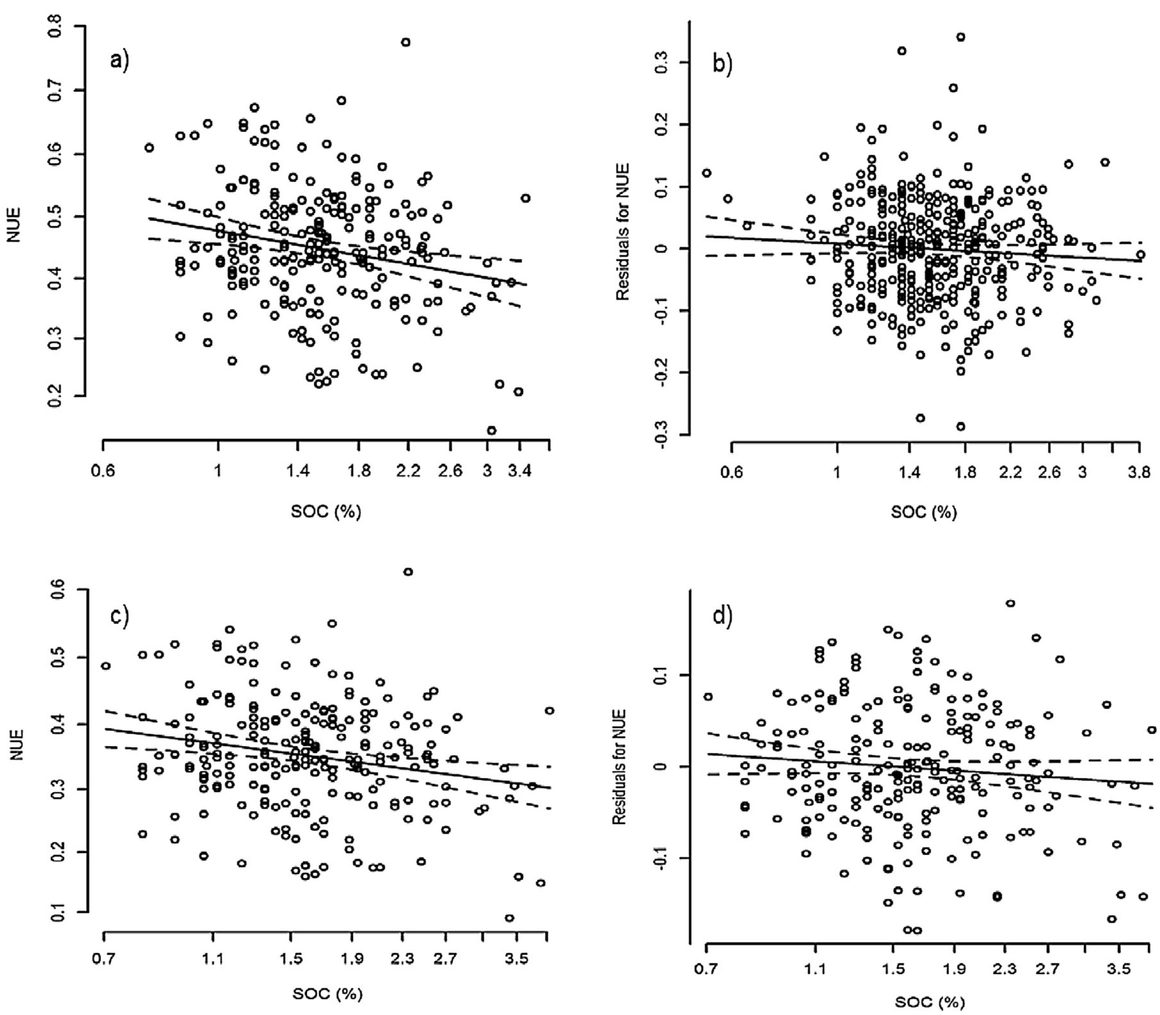

Fig. 5. Nitrogen use efficiency (NUE) in winter wheat (a) and spring barley (c), respectively as a function of SOC, and residual plots for winter wheat yields (b) and spring barley yields (d) for N use efficiency as a function of SOC (note the axes are transformed). The solid line is the estimated regression line, whilst the dotted lines demonstrate the 95% confidence interval.

Table 7
Estimates, 95% confidence intervals (CI) and *p*-values for the parameters on the transformed covariates in the final model for the transformed NUE in winter wheat.

	Estimate	CI lower	CI upper	*p*-value
(Intercept)	0.1736	0.0533	0.2939	0.0048
Soil organic carbon	−0.1703	−0.2593	−0.0814	0.0002
Mean spring global radiation	0.1181	0.0277	0.2086	0.0106
Mean winter precipitation	0.2822	0.1824	0.3820	0.0000
Mean summer temperature	0.1103	0.0203	0.2003	0.0164
(Mean winter precipitation)^2	−0.0829	−0.1513	− 0.0146	0.0175
(Mean summer precipitation)^2	−0.1220	−0.1991	−0.0449	0.0020

depicting how much variation SOC explains in the final model was 0.001.

The plot of spring barley $YIELD_{N0}$ as a function of SOC, presented in Fig. 4c, shows a slightly negative relation, although it is not significant ($p = 0.13$). However, the residual plots of potential $YIELD_{N0}$ as a function of SOC for spring barley (Fig. 4d), based on the full model where SOC was excluded, exhibited a slight positive relationship, although not significant ($p = 0.12$). In the full statistical model including all the other explanatory variables, the effect of SOC was highly significant ($p = 0.0080$).

Parameter estimates for the final model of yields of spring barley without fertiliser N application ($YIELD_{N0}$) ($R^2 = 0.45$) are presented in Table 6. The relation between SOC and $YIELD_{N0}$ was significantly different between the specific soil types indicating an interaction between SOC and soil types ($p = 0.0050$). A significant effect of SOC was found for soil type JB1 (positive influence, adjusted $p = 0.0054$), and a borderline significant effect of SOC was found for soil type JB5 (positive influence, $p = 0.0370$, adjusted $p = 0.1110$). The R^2 value for the marginal contribution of SOC to the final model was 0.008.

3.3. The effect of SOC on NUE in winter wheat and spring barley

Plots of the relationship between NUE and SOC for winter wheat and spring barley, presented in Fig. 5a and c, respectively, reveal a significantly negative relation in both cases ($p < 0.0001$ for winter wheat and $p < 0.001$ for spring barley). The residual plots of NUE as a function of SOC, based on the full model where SOC was excluded, for winter wheat and spring barley (Fig. 5b and d) further demonstrate this negative relationship. In the full model containing all other explanatory variables the effect of SOC was borderline significant for winter wheat ($p = 0.06$) and not significant for spring barley ($p = 0.35$).

Parameter estimates for the final model of NUE of winter wheat ($R^2 = 0.21$) and spring barley ($R^2 = 0.26$) are presented in Tables 7 and 8, respectively. A significant negative influence of SOC on NUE was found for both winter wheat ($p = 0.0002$) and for spring barley ($p = 0.015$). R^2 values for how much variation SOC explains in the final model were 0.07 and 0.04 for winter wheat and spring barley, respectively.

4. Discussion

4.1. Potential yields, non-fertilized yields and SOC

One of the hypotheses of this study was that an increased level of SOC leads to an increase in potential yields i.e., the yield that can be attained when sufficient levels nutrients are available to not limit biomass production. The results presented in this study do not support this hypothesis – only for soil type JB5, in spring barley, we found a borderline significantly positive effect of SOC on potential yields (Table 4). These results are surprising, given that it is widely agreed that SOC has positive effects on crop productivity. Loveland and Webb, 2003, also focusing on temperate regions, demonstrate that SOC reduction only leads to a small reduction in yield potential. Loveland and Webb, 2003 further explored the notion of a critical value of SOC of 2% below which a decline in soil quality would occur in temperate regions. They found no quantitative evidence to support such a threshold, instead they discussed a desirable range of SOC content. In the current study we only had 18 sites cropped to wheat and 11 sites cropped to barley with a SOC content below 1% and therefore we do not have a good basis for assessing the validity of this threshold. Looking at Fig. 3, there could be some support for a threshold around 0.8% SOC for winter wheat, but this is only supported by four sites. For barley there is no support for a threshold below which potential yields collapse.

Körschens et al., 1998 analyzed the results from 13 European long-term experiments designed to discern the effects of SOM contents on yields. The contribution of SOC to crop yield was estimated to be less than 10%, by which the authors mean that at least 90% of potential yield can be obtained on sandy soils with addition of mineral fertilisers, and 95% of potential yield on loamy soils.In a wider analysis of long term experiments, Körschens et al., 2013 found that the SOM effects on yields of winter wheat were in the order of 3%. This implies that 90 to 97% of potential yields can be obtained by adding sufficient mineral fertiliser. As indicated above, in the analysis of potential yields we are analyzing nutrient unlimited yields because the potential yield is the yield attained at sufficient nitrogen application and we assume other nutrients to be non-limiting. Under nutrient limiting conditions, the effect of SOC might be expected to be more pronounced because mineralization from a larger SOC pool should be able to supply more nutrients.

One might raise the issue of whether all potential confounding variables have been accounted for in the statistical analysis. There may be an influence of farm type linked to farm management, a variable we were unable to include in our analysis. For example, a dairy farmer in Denmark would typically have a higher proportion of grassland in their rotation than an arable farmer. This would lead to an accumulation of organic matter and thus higher soil carbon content. However, a dairy farmer may not have as strong a focus on crop management and yield optimisation as a typical arable crop farmer, and thus may have lower potential yields (despite having a higher SOC) due to suboptimal timing of management, crop protection etc. In general, the recent cropping history especially the presence of grass leys could affect the results significantly and inclusion of more information about this could strengthen the analysis. Another confounding variable may be soil drainage. Poorly drained soils tend to have high contents of SOC because of less conducive conditions for decomposition of soil organic matter. Transient waterlogging has been shown to have negative effects on crop yields, for example due to restricted root development and increased N loss by denitrification and leaching (Jiang et al., 2008; Zhang et al., 2006). In our analysis, we attempted to account for drainage status by including altitude as a variable under the assumption that low altitudes will have poor drainage. Altitude may not be a good proxy for of drainage status, but no better information was available for the national field trials dataset.

Table 8
Estimates, 95% confidence intervals, *p*-values, and adjusted *p*-values for the parameters on the transformed covariates in the final model for the transformed NUE in spring barley.

	Estimate	CI lower	CI upper	*p*-value	Adjusted *p*-value*
(Intercept)	0.9124	0.2835	15.414	0.0047	–
Soil organic carbon	−0.1625	−0.2932	−0.0318	0.0150	–
Mean winter precipitation	−0.1653	−0.2982	−0.0324	0.0150	–
Mean summer precipitation	−0.1906	−0.3135	−0.0677	0.0025	–
Mean summer temperature	0.2718	0.1473	0.3964	0.0000	–
Irrigation	19.809	0.7911	31.707	0.0012	0.0024
$(\text{Irrigation})^2$	−0.9450	−15.609	−0.3291	0.0028	0.0028
$(\text{Altitude})^2$	−0.0980	−0.1752	−0.0208	0.0131	–
$(\text{Mean winter temperature})^2$	0.0836	0.0089	0.1583	0.0285	–

* Adjusted *p*-value excluded when the value is the same as *p*-value.

Our analyzes showed that crop yields were reduced with higher altitude, thus indicating that altitude was indeed a poor proxy for water logging, and that better soil water supply in low-lying areas supported crop yields.

Johnston et al., 2009 recognized the challenge in identifying and quantifying clear effects of different historical soil organic matter inputs contributing to soil fertility, in particular the precise effects of SOM on yields. A pertinent question is which attributes of SOM may contribute to improving yields, e.g., are increased yields at higher SOM levels a result of increased nutrient availability following increased mineralisation (for example demonstrated by Johnston et al. (2009), or do they result from SOM effects on soil physical qualities (see for example Schjønning et al. (2012). The role of SOC in improving soil quality is also attributed to its role in improving soil physical properties. Schjønning et al., 2009 argue that whilst a common threshold cannot be delineated for SOC, low levels of SOC can have serious implications for aggregate stability. In the Hoosfield continuous barley experiment, the authors attribute the observed higher yields in fields with higher SOM levels primarily to improved soil structure from SOM, although they recognize the potential addition of N mineralized late in the season (Johnston et al., 2009). Thomsen and Christensen (2004) attributed increased yields of winter wheat to effects other than increased N availability. Alvarez and Grigera, 2005 found, in the Argentinian Pampas, that growing season precipitation was strongly correlated with wheat yield, whilst organic matter had no detectable influence on wheat yields. However, they predicted an indirect effect of SOM on yields as SOM correlated with initial soil N levels.

We hypothesised that the yields of winter wheat and spring barley with no fertiliser N application would be positively affected by SOC level. The relationship between unfertilized plot yields and SOC was positive for winter wheat (parameter estimate was 0.059), although not significant, whilst for spring barley a significant positive effect of SOC was found only for soil type JB1, and a borderline significant positive effect of SOC was found for soil type JB5. The results of this analysis were surprising, because we expected a significant positive effect of SOC in both cases based on a presumed importance of nutrient supply from the soil organic matter when no mineral fertiliser N was applied. However, a large variation in zero N application yields was evident in data for both winter wheat and spring barley, as seen from Fig. 3a and c, ranging from very low yields, demonstrating N deficiency, to yields seemingly unlimited by N. Although data on the total N applied in manure, biosolids, waste composts was included, no data on preceding crop history was included as variables in the analyzes. This could have a large influence, especially for the YIELDN_0 without other nutrient inputs, e.g., whether the preceding was a grass-clover pasture or a cereal. For spring barley grown on soil type JB1 where a significant effect of SOC was observed, SOC most likely plays an important role in improving buffering capacity as well as nutrient retention and release.

Our hypothesis was based on the expectation that yield with no N fertilizer application would depend on N-mineralisation, and that the amount of SOC present has a significant effect on this. For example, Johnston et al., 2009 demonstrated in the long term trials in Woburn and Hoosfield that yields in the absence of fertilizer N were larger on soils with higher levels of SOM. In our case, it may not only be the amount of SOC that is decisive for N mineralisation, but also SOC quality that determines the potentially mineralizable N. For example, in their review, Loveland and Webb, 2003 discuss the importance of the proportion of active (fresh) carbon added, suggesting that the proportion of 'fresh' carbon in the total C pool may be of greater importance than the size of the C stock itself. There may be significant variation across soil types in the proportion of SOC that is inert and thus does not contribute to soil N. Additionally, the data analyzed did not include a variable accounting for the potential contribution of nitrogen from the previous crop. For example, whether the previous crop was grassland or cereal might have an effect on yields of the following crop when no other N is added. The analysis was based on total SOC and did not differentiate between different fractions of SOC. As such, the results may not capture the indirect effects on plant growth (through increased microbial activity) of the light fraction of SOC.

4.2. NUE and SOC

The tested hypothesis was that an increase in content of SOC leads to an increase in NUE. As far as we are aware, nutrient use efficiency has not previously been reported as a function of SOC. SOM could be expected to have an indirect effect on NUE, given that high rates of N mineralization, as would be expected in soils high in SOC, would increase levels of plant available N in all treatments, thus increasing the N uptake in the low N fertilizer treatments (Ladha et al., 2005). If N crop demand and N fertilizer applied remain constant, an increase in net N mineralization will decrease NUE (Ladha et al., 2005). However, if SOC improves soil physical properties and nutrient retention characteristics, it may also be expected to improve NUE. In the current study, a significant negative relationship was found between SOC and NUE for both winter wheat and spring barley,which was counter to what we had hypothesised. The effects of N supply from SOC mineralization appear to be more important than the ability of SOC to improve N retention characteristics. However, this explanation does not align with the results of the analysis for the zero N application yields. Therefore, when considering the efficiency of N use, it is important to account for residual effects from the interplay between soil carbon and N mineralization from previous crops and organic amendments.

4.3. Merits of the approach taken in the current paper

The effect of SOC on potential crop yields was investigated using experiments from a wide range of different sites with annual field trials undertaken in the past 20 years. This approach holds some advantages over long-term experiments conducted at the same site, with treatments gradually changing the amount of SOC, but also holds some disadvantages. The primary advantage is that the large number of sites enables many more combination of soils, climate and management conditions to be included, which is obviously not possible for long-term experimental sites. This means that the results are more likely to be generally valid than results from a few sites and limited number of treatments which has been used to change the content of SOC. One might argue that the results from a few sites are not valid for other sites, e.g., with a different soil type or if the change in organic matter had been inflicted with another amendment. The disadvantage is that the statistical analysis is complicated by the confounding variables, and therefore is much less stringent. Therefore we believe that both approaches have their merits in helping us understanding the very complicated effects of SOC on crop yields and should both be employed in pursuit of this understanding. As discussed above, an important variable which was not included in our analysis was the previous cropping history, which could be another confounding factor. Leys are likely to be more widespread on the sandy soils in Denmark, which have high organic matter contents. If leys improve yields in the subsequent crops this should produce an apparent positive effect of organic matter. As we have been unable to test this we have not included any discussion about this.

5. Conclusion

We tested the effect of SOC on three response variables (potential yields, yields with no N fertilizer application and N use efficiency) for winter wheat and spring barley. Our analysis revealed a slightly negative, but not statistically significant relationship between SOC and potential winter wheat yield when the effect of potential confounding variables was accounted for. Regarding potential yields of spring barley, a significant interaction between SOC and soil type was found. For yields at no N fertilizer application, the analysis revealed an effect of SOC which was positive but not statistically significant for winter wheat whilst for spring barley, the relationship with SOC was significantly different between soil types. The N use efficiency was negatively correlated with SOC for both crop types investigated.

The results of the analysis of the effect of SOC on potential yields were contrary to what we had expected and what is widely held regarding the importance of SOC in crop productivity. One might therefore, based on the large dataset analyzed, cautiously challenge the importance of SOC in contributing to crop productivity in environments with similar soils and climate. In particular, very few of the soils included in this study had a SOC level below 1%, which may be considered a lower threshold. Given the few observations under 1% in our dataset, we could not explore the yield effects in this specific range. However, in light of the generally observed effect of SOC on potential yields in our data, we could speculate that in situations where nutrient limitation does not occur, SOC levels above 1% may be sufficient to sustain yields.

However, it is important to recognise that this will not necessarily be the case in instances where cropping systems rely heavily on nutrient supply from SOC mineralization–such as organic farming and other types of low input agriculture. Furthermore, such a low threshold does not necessarily reflect how much carbon such soils can, or should, sequester for other ecosystem services.

In light of the findings presented in this study, further work should be conducted which can further elucidate the effect of SOC on yields. Long-term field experiments are indispensable to test the effect of SOC on yields, but the validity of the results are obviously limited to the few sites, soil types, SOC contents, nutritive and climatic conditions under which the experiments have been conducted. The current approach, where results of nutrient response experiments in a large number of sites are analyzed, has the disadvantage that SOC is confounded with other variables such as clay content, but also clearly provides some additional information and understanding, which can contribute to the knowledge generated from the long-term experiments.

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