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RESEARCH ARTICLE

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Limitations of farm management data in analyses of decadal changes in SOC stocks in the Danish soil-monitoring network

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Abstract

Changes in soil organic carbon (SOC) storage in agricultural land are an important part of the Land Use, Land-Use Change and Forestry component of national greenhouse gas emission inventories. Furthermore, as climate mitigation strategies and incentives for carbon farming are being developed, accurate estimates of SOC stocks are essential to verify any management-induced changes in SOC. Based on agricultural mineral soils in the Danish soil-monitoring network, we analysed management effects on SOC stocks using data from the two most recent surveys (2009 and 2019). Between 2009 and 2019, the average increase in SOC stock was 1.2 Mg C ha^{-1} for 0–50 cm despite a loss of 1.2 Mg C ha^{-1} from the topsoil (0–25 cm), stressing the importance of including deeper soil layers in soil-monitoring networks. Comparing all four national surveys (1986, 1997, 2009, 2019), the mean SOC stock of mineral soils in Denmark appears stable. The change in SOC stock between 2009 and 2019 was analysed in detail in relation to management practices as reported by farmers. We found that the effects of single management factors were difficult to isolate from co-varying factors including soil parameters and that the use of farm management data to explain changes in SOC stocks observed in soil-monitoring networks appears limited. Uncertainty in SOC stock estimates also arises from low sampling frequency and statistical challenges related to regression to the mean. However, repeated stock measurements at decadal intervals still represent a benchmark for the overall development in regional and national SOC storage, as affected by actual farm management.

KEYWORDS

carbon stock changes, national soil survey, perennial crops, ploughing, soil organic carbon, straw incorporation

1 | INTRODUCTION

Quantifying soil organic carbon (SOC) stocks at regional and national scales are needed for national greenhouse gas (GHG) inventories, such as those required by the UNFCC, EU climate policy and the Kyoto Protocol (European Commission, 2013; UNFCCC, 1997). Likewise, it is essential to have accurate estimates of SOC stocks and their changes in time for GHG markets and future schemes of carbon credits (European Commission, 2022; McDonald et al., 2021). In this respect, documented links between changes in SOC stock and specific land uses and management activities could potentially guide future legislation and practices towards more carbon-neutral agriculture (Smith, 2008).

One way to estimate SOC stocks and their change at a regional or national level is soil-monitoring networks, which have been set up in several countries for both forests and agricultural soils (Callesen et al., 2015; Knotters et al., 2022; Nerger et al., 2020; O'Sullivan et al., 2017; Poeplau et al., 2020; Rutgers et al., 2009; Smith et al., 2020; Spencer et al., 2011; Taghizadeh-Toosi et al., 2014; Van Wesemael et al., 2010). In 1986, a national soil-monitoring network, the National Square Grid (NSG), was established in Denmark to document annual levels of soil mineral nitrogen (N) across different soil types (Østergaard & Mamsen, 1990). Approximately once per decade, a comprehensive sampling campaign has been performed in the NSG with the aim to measure SOC stocks and their changes in time (Heidmann et al., 2002; Taghizadeh-Toosi et al., 2014). Concurrently, information on farmer management practices has been collected, potentially allowing for the analysis of links between SOC changes and soil management.

It is well-documented that agricultural management affects SOC stocks, as the crop type determines the quality, quantity and location (aboveground, belowground) of the carbon (C) input to the soil (Bolinder et al., 1997; Ledo et al., 2020). In addition, the use of cover crops, straw incorporation and application of organic fertilizers may increase SOC stocks (Gross & Glaser, 2021; Jensen et al., 2022; Poeplau & Don, 2015). These effects may be quantified in long-term field experiments where given management is maintained for several years or decades (Christensen et al., 2022; Hu et al., 2019). However, long-term experiments testing individual management elements may not reflect agricultural farming practices with frequent changes in cropping sequences and soil management. It therefore becomes important to verify changes in SOC stocks as affected by actual management, for example, by using soil-monitoring networks where agricultural management covers a range of practice-oriented choices, geographical regions and soil conditions.

Highlights

- Soil organic carbon (SOC) stock (0–50 cm) increased by 1.2 Mg C ha^{-1} between 2009 and 2019.
- Subsoil gains outweighed topsoil losses, stressing the importance of subsoil analyses.
- Average national SOC stocks were relatively stable between 1986 and 2019.
- Inter-correlated farming practices challenge verification of management effects in monitoring networks.

One approach to link SOC stock changes to farm management is to collect soil samples from sites across a spectrum of specific management practices, for example, as done by Gubler et al. (2019). They looked at SOC stocks at sites where the fraction of perennial crops spanned from <20% to permanent grasslands. Another approach combines field data from surveys with satellite imagery, as done by Bricklemyer et al. (2007). These approaches focus on areas subject to specific management, and may therefore not represent the actual variation in farm management strategies across the region of study. Linking national or regional soil C surveys with information on actual farm management through statistical analysis may help to understand the farm-scale effects of the different management activities and crops on observed changes in SOC.

Based on soils sampled in 2009 and 2019 in the Danish NSG, combined with management and crop information reported by farmers during the same 10-year period, we aimed to quantify (1) changes in SOC stocks between 2009 and 2019, and (2) isolate effects of individual management practices on SOC changes using statistical analysis. Further, we assessed changes in SOC stocks from 1986 to 2019 based on NSG sites included in the present study and two previous nationwide soil surveys (Taghizadeh-Toosi et al., 2014).

We hypothesize that (1) SOC stocks in Danish agricultural soils decreased between 2009 and 2019, and (2) that farm management practices that increase crop cover duration (perennial crops, autumn-sown crops) and well as retaining biomass on the field (straw incorporation) have positive effects on the SOC stock.

2 | MATERIALS AND METHODS

2.1 | Study area

The sites in the NSG are arranged in a 7 km by 7 km grid that covers the entire Denmark, including different ecosystems, such as agricultural soils, forests and heathlands (Østergaard & Mamsen, 1990). Only agricultural sites on mineral soils are included in this study. The original number of agricultural sites was 608, which were sampled in 1986. Subsequent campaigns (1997, 2009 and 2019) had fewer sites accessible and consequently, 395 sites were sampled in both 2009 and 2019 (Figure 1), while 229 sites were included in all four national sampling campaigns.

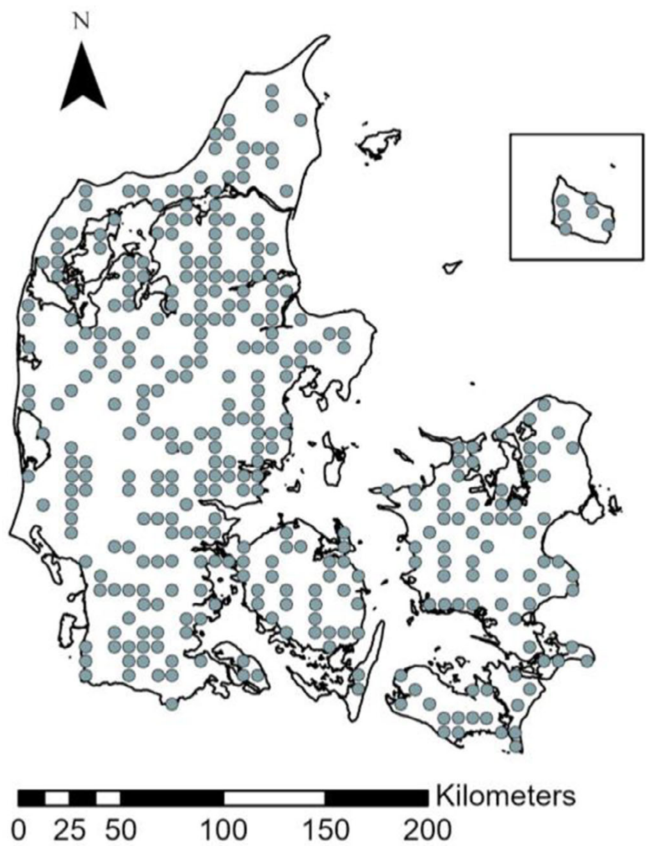

FIGURE 1 Map of the NSG sites sampled in both 2009 and 2019.

The soils of central and eastern Denmark are Cambisols and Luvisoils with a higher clay content than the coarse-textured soils of western Denmark, which typically classify as Alisols, Arenosols and Podzols, and with Gleysols in the north-western region (Adhikari et al., 2014; Harbo et al., 2022). The central and eastern parts of Denmark classify as warm, humid continental climate (Köppen: Dfb), while the western part classifies as temperate, marine west coast climate (Köppen: Cfb). The mean annual air temperature and precipitation in Denmark during 1991–2020 was 8.7°C and 759 mm, respectively (DMI, 2022). The most common crops in Denmark are autumn-sown and spring-sown cereals, notably winter wheat (*Triticum aestivum* L.) and spring barley (*Hordeum vulgare* L.), as well as perennial grasses (Statistics Denmark, 2023). Cover crops are encouraged and in some cases mandatory by Danish legislation (Aronsson et al., 2016; Landbrugsstyrelsen, 2022).

In Denmark, arable mineral soils are usually classified according to soil type category (*Jordbundskategori*: JB scheme) in which topsoil (0–25 cm) texture determines the category based primarily on clay content (Table 1). The soils of sites included in this study categorize into JB1–JB7, which represent 93% of the Danish agricultural area. Operationally, the categories JB1–JB4 (<10% clay) and JB5–JB7 (10–25% clay) are grouped as sandy and as loamy soils, respectively. We excluded NSG sites with soils having >25% clay or >6% SOC (organic soils) as these are so few in number that the statistical analysis would be deflated by the sample size.

2.2 | Soil sampling in the National Square Grid

The two most recent nationwide soil samplings in the NSG took place in the autumn-winter periods 2008–2009 (here referred to as 2009) and 2018–2019 (here referred to as 2019) and included 395 sites that were sampled in both years.

TABLE 1 Textural soil classification according to the Danish JB scheme (Madsen et al., 1992).

		Weight percent (%)			
Soil category	**JB**	**Clay <2 μm**	**Silt 2–20 μm**	**Fine sand 20–200 μm**	**Sand, total 20–2000 μm**
Sand	1	0–5	0–20	0–50	75–100
	2			50–100	
	3	5–10	0–25	0–40	65–95
	4			40–95	
Loam	5	10–15	0–30	0–40	55–90
	6			40–90	
	7	15–25	0–35		40–85

At each NSG site, a 50 m by 50 m grid was subdivided into 100 cells of 5 m by 5 m, and 16 of these cells were randomly chosen a priori for soil sampling. The same 16 cells were sampled in 2009 and 2019. Sampling was performed with a 1 cm inner-diameter soil auger, and topsoil (0–25 cm) and subsoil (25–50 cm) from the 16 cells were pooled for one SOC analysis per site, soil layer and year. In a few cases with hard subsoils, a percussion auger (5 cm diameter) mounted on a Gator Utility Vehicle (John Deere) was used.

In addition to samples for SOC analysis (taken from 16 cells), undisturbed 100-cm^3 cores (height, 3.5 cm; diameter, 6.1 cm) for determination of bulk density were sampled from four other 5 m by 5 m cells at each NSG site in 2019. For each of the four cells, one soil core was taken in the middle of the 0–25 cm layer and one was taken in the middle of the 25–50 cm layer using metal rings that were hammered into the soil using a special flange to ensure horizontal orientation. This provided average soil bulk density estimates at each NSG site for depths of 11–14 cm and 36–39 cm. Soil bulk density and the volumetric rock content were determined as described by Harbo et al. (2022).

2.3 | Management data

Yearly information on crop species, sowing times, presence and species of cover crops, the timing of ploughing or tillage events, and use of mineral fertilizer and animal manure (including application times, rates, and origin) for each sampling site were reported by farmers and stored in a management database by the agricultural knowledge and innovation centre SEGES. The data were carefully inspected for use in the present study since some of the self-reported information was incomplete and associated with uncertainties. Of the 395 sites, management data for 224 sites covered all years between 2009 and 2019 and were qualified for statistical analyses. The resulting agricultural management information was divided into three operational categories: main crops, field activities, and fertilization.

2.3.1 | Main crops

Each main crop registered in the annual survey was categorized according to crop type and sowing time as either (1) "autumn-sown crops", including winter cereals and rapeseed (*Brassica napus* L.), (2) "spring sown crops", including spring-sown cereals, most vegetables, herbs and flowers, (3) "perennial crops", including grasses and perennial plant mixtures, (4) "maize" exclusively containing silage maize (*Zea mays* L.), or (5) "root crops", including potatoes (*Solanum tuberosum* L.), carrots (*Daucus carota* L.) and beets (*Beta vulgaris* L.).

Some crops were identified as cover crops in the survey, either by the registered species name or by the time of sowing in relation to preceding and subsequent crops. Occasionally, the cover crop was grown to establish a grass or grass-field crop that was maintained for more than one winter season. In this case, the crop was registered as a cover crop in the year of establishment and as a perennial crop in subsequent years.

2.3.2 | Field activities

Field activities were grouped as ploughing or tillage (here referred to as ploughing), straw incorporation and cover cropping. The variables were quantified in the following way: "Ploughing" is the number of times the soil has been ploughed during the 10-year period (fields may be ploughed more than once per year); "Straw incorporation" is the number of years with straw retained in the field; and "Cover cropping" is the number of years with cover crops.

2.3.3 | Fertilization

Data on the frequency, type, and timing of mineral and organic fertilizer application (including animal manures) were available in the management database, but the annual amounts applied were not consistently reported. However, Denmark has strict regulations on the application of N that relates mainly to soil type and crop (Danish EPA, 2017), and farmers typically apply the maximum allowed N rate every year. Thus, we relate any effect of fertilization to the fertilizer category. As only organic fertilizers provide organic C to the soil, the use of mineral fertilizer was not included in the statistical analysis. The organic fertilizers were divided into "cattle", including manure from both dairy and meat production, "pig" which covers all types of pig manure, and "other", which covers all other sources of animal manure, for example, chicken, mink and sheep, as well as organic waste from industry and municipalities, and digested mixed manures.

2.4 | SOC stock calculation

Based on the SOC data reported by Taghizadeh-Toosi et al. (2014) for 1986, 1987 and 2009 and data for SOC, bulk density (BD) and rock fragment contents (RF) for 2019 reported by Harbo et al. (2022), we calculated the

SOC stock at each site for both the topsoil (0–25 cm) and subsoil (25–50 cm):

$$SOC\,stock_x = C_{i,x} {}^* BD_{fine,i} {}^* d_i {}^* (1 - RF_i) \quad (1)$$

where x is one of the four soil surveys (1986, 1997, 2009 and 2019), $C_{i,x}$ is the organic C content (%) of the fine soil (<2 mm) of the ith soil layer at time x, $BD_{fine,i}$ is the site-specific bulk density (Mg m^{-3}) of the rock fragment-free fine soil fraction of the ith soil layer, d_i is the depth of the ith soil layer in cm, and RF_i (unitless) is the corresponding volumetric rock fragment content of the ith soil layer. Site-specific BD measured in 2019 was assumed to be a reliable estimate of BD at the previous samplings where this parameter was not measured directly.

If the change in SOC stock between 2009 and 2019 was greater than 20 Mg C ha^{-1}, the site was excluded from the statistical analysis, due to concerns of errors related to regression to the mean (Slessarev et al., 2023); meaning that for any repeated measurement on the same subject, an extreme (too high or too low) observation is more likely to be followed by a less extreme observation (closer to the "true value") (Barnett et al., 2005). The value of 20 Mg C ha^{-1} corresponds to a yearly change of ±2 Mg C ha^{-1}, which is an unlikely change in the SOC stock of mineral soils under typical Danish farming practices. Based on this criterion, 43 sites were excluded, leaving 352 sites for statistical analysis of changes in SOC stock.

2.5 | Parameter selection for the statistical model

2.5.1 | Soil parameters

The soil parameters used for the statistical analysis are fine soil bulk density and rock fragment content (unitless), which were both measured during the 2019 survey and clay content (weight %) which was measured in 1986. Furthermore, the mean SOC stock between 2009 and 2019 was used as a proxy variable for the SOC stock. The mean rather than the difference was used since the difference between any two numbers is inherently correlated with both numbers and thus the change in SOC stock between 2009 and 2019 is not independent of either number.

2.5.2 | Management parameters

The statistical model includes the number of years with each main crop. However, as each site has 10 years of crop information, the crop data is of a closed-compositional nature; the sum of all crop categories must equal 10. Closed-compositional data is problematic for applying statistical and analytical methods, as assumptions about an unconstrained Euclidian sample space are violated (Aitchison, 1982; Pawlowsky-Glahn & Egozcue, 2006). To avoid this, the crop categories "Maize" and "Root crops" were excluded from the dataset. As maize and root crops account for <7.5% of the site years (number of years across all sites), only a small part of the dataset was excluded. To avoid the effects of too few years of crop information on the statistical model, sites with <6 years of crop information (8 sites) were excluded, leaving 216 sites for use in the statistical model.

2.6 | Data analysis and statistics

Linear models were used to determine the relationship between average SOC stock (2009–2019) and the observed change in SOC stock.

Correlations between soil parameters and between management parameters were analysed using Spearman's correlation coefficient.

Generalized least squares models (GLS) were applied to determine the effect of soil parameters, crop categories and management activities on the SOC change. To determine if the data set had spatial autocorrelation, semi-variograms were fitted to the GLSs and the correlation was assessed visually. It was found that spatial autocorrelation was unimportant as the semi-variograms showed no spatial correlation for the fitted model. Thus correction of spatial autocorrelation in the GLSs was not necessary and a simple linear model could be fitted instead.

All calculations were performed in R 4.0.4 (R Core Team, 2021). GLS and semi-variograms were calculated using the "nlme" package (Pinheiro et al., 2022), and Spearman's correlation coefficient was calculated using the "psych" package (Revelle, 2022).

3 | RESULTS

3.1 | Changes in SOC stocks during 2009–2019

The mean SOC stock in the 0–25 cm topsoil across all soil categories was 57.3 and 56.1 Mg C ha^{-1} in 2009 and 2019, respectively (Figure 2, Table 2), indicating a loss of 1.2 Mg C ha^{-1} ($P < 0.05$). In the 25–50 cm subsoil, the SOC stock was 35.0 Mg C ha^{-1} in 2009 and 37.3 Mg C ha^{-1} in 2019, that is, indicating an increase of 2.3 Mg C ha^{-1} ($P < 0.05$). Overall, the sandy sites had greater SOC stocks compared to the loamy sites in both the topsoil and subsoil in both years ($P < 0.05$).

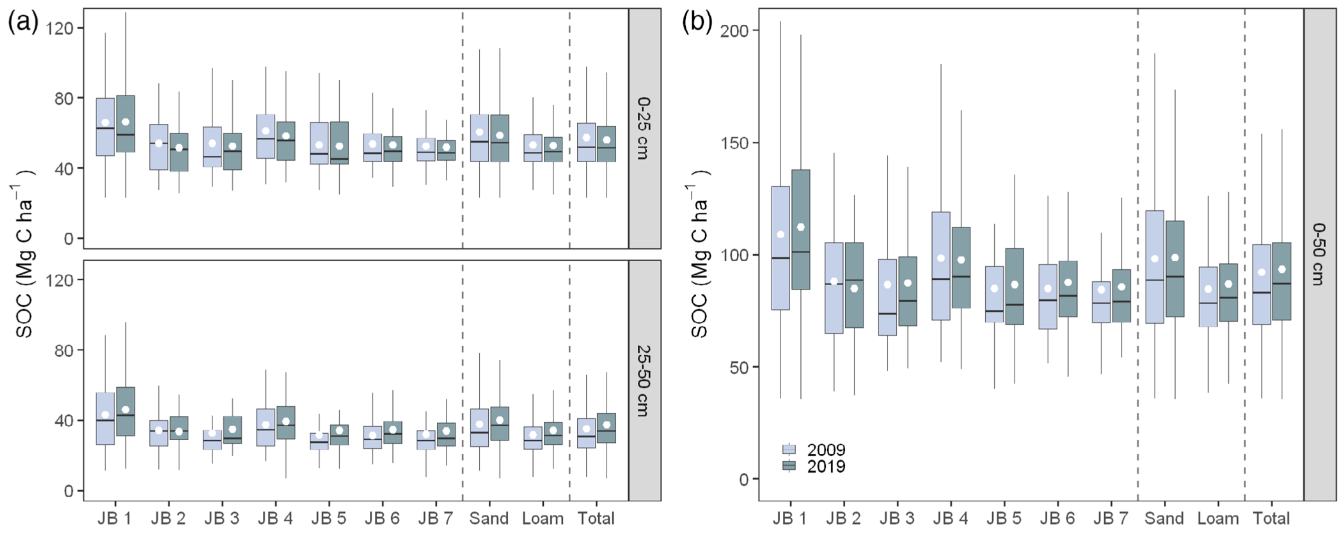

FIGURE 2 Box plots of SOC stock estimates (Mg C ha^{-1}) for each JB category, soil group (Sand and Loam) and for all observations (Total) for A) the 0–25 cm and 25–50 cm soil layers, and B) the combined 0–50 cm soil layer. Data for 2009 is shown in light blue, while data for 2019 is shown in dark blue. The horizontal line in the boxes is the median; the white circle is the mean. The lower and upper boundary of the box is the first and third quartile of the dataset. The whiskers extend to the furthest observation within 1.5 times the interquartile range. Outliers are omitted for visual clarity but were included in the analyses.

TABLE 2 Mean change in soil organic carbon (SOC) stock (Mg C ha^{-1}) between 2009 and 2019 for each JB category and depth interval (and in total), as well as the percentage of points that gain SOC stock between 2009 and 2019. Number of observations for each soil category is shown in parentheses.

	Change in SOC stock (Mg C ha^{-1})							
Depth interval	**JB1 (55)**	**JB2 (22)**	**JB3 (34)**	**JB4 (86)**	**JB5 (15)**	**JB6 (87)**	**JB7 (53)**	**Total (352)**
0–25 cm	0.4	−2.8	−1.6	−2.7	−0.7	−0.4	−0.7	−1.2
25–50 cm	2.9	−0.6	2.2	2.1	2.4	3.2	1.9	2.3
0–50 cm	3.3	−3.4	0.6	−0.6	1.7	2.8	0.2	1.2
	Percentage of sites that have gained SOC							
0–25 cm	51%	14%	41%	35%	40%	48%	47%	42%
25–50 cm	69%	55%	68%	64%	73%	70%	60%	66%
0–50 cm	65%	45%	56%	51%	60%	63%	55%	57%

In the topsoil, all soil JB categories on average lost SOC between 2009 and 2019, except for JB1 (Table 2), which nevertheless showed a decrease in the median SOC stock (Figure 2). Despite the average SOC losses, 14%–51% of the sites within a given JB category gained SOC in the topsoil (Table 2). In the subsoil, all soil categories on average gained SOC between 2009 and 2019 (except for JB2). However, within each JB category, 27%–45% of the sites actually lost SOC in the subsoil (Table 2).

Across the whole profile (0–50 cm) and all soil categories there was an average net increase of 1.2 Mg C ha^{-1} ($P = 0.056$); only JB2 and JB4 showed a decrease in the mean SOC stock. Meanwhile, all soil categories showed an increase in the median SOC stock (Table 2, Figure 2). The distribution of sites either gaining or losing SOC stock (0–50 cm) between 2009 and 2019 was relatively even; across the soil categories, 57% of sites gained and 43% lost SOC stock. Clearly, the mean change in SOC stock may not be representative of individual sites.

For the topsoil, there was a significant negative relationship between the change in SOC between 2009 and 2019 and the average SOC stock of the two surveys (Figure 3), meaning that sites with larger average stocks have lost SOC more frequently than sites with smaller average stocks. This relationship was, however, not observed for the subsoil.

3.2 | Effect of management on SOC stocks

3.2.1 | Parameter exploration

Autumn-sown crops were the most frequent crop type at both sandy and loamy sites across Denmark, followed by spring-sown crops and perennial crops (Figure 4).

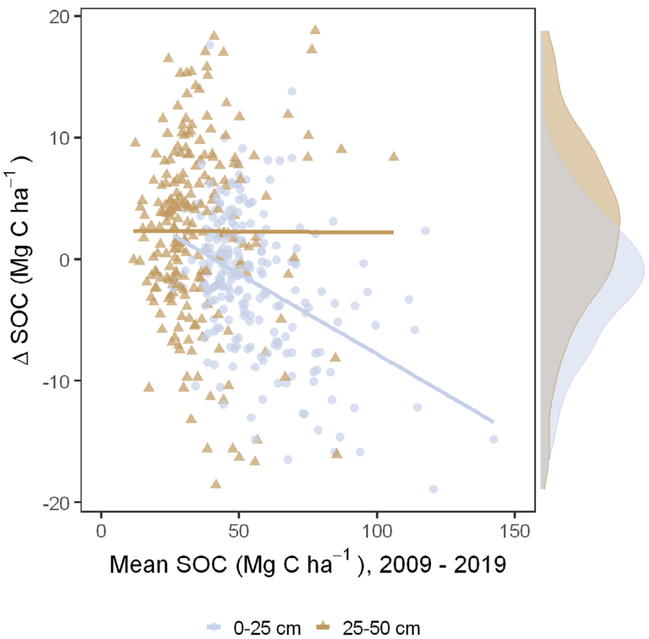

FIGURE 3 Change in soil organic carbon (SOC) stock (Mg C ha^{-1}) between 2009 and 2019 in relation to the average SOC stock (Mg C ha^{-1}) in 2009 and 2019 for the topsoil (light blue circles) and subsoil (brown triangles). A linear relation between the change in SOC stock and average SOC stock is fitted to each soil layer. The distribution of changes in SOC stock between 2009 and 2019 for the topsoil (light blue) and subsoil (brown) is shown on the right-side y-axis.

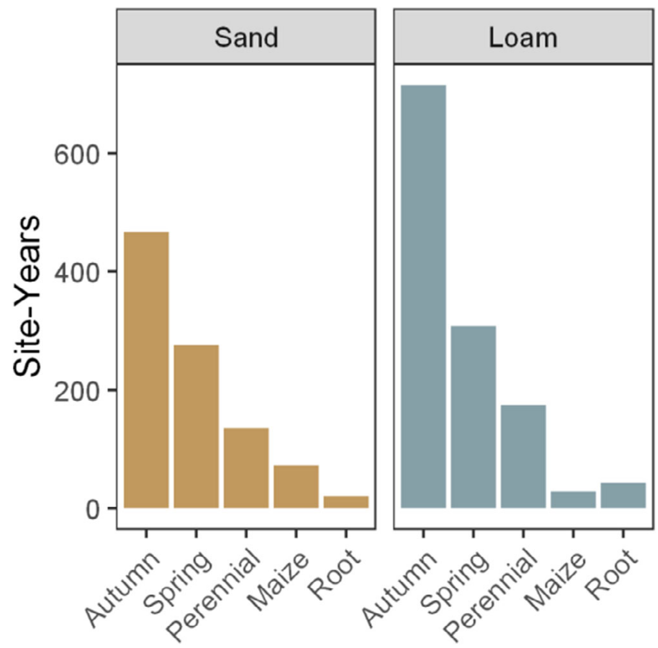

FIGURE 4 Total site-years of each crop type for sandy (JB1–JB4, $n = 97$) and loamy (JB5–JB7, $n = 127$) soils between 2009 and 2019. The crop categories are autumn-sown crops (Autumn), spring-sown crops (Spring), perennial crops (Perennial), maize (Maize), and root crops (Root).

Maize was more frequent on sandy than loamy sites, whereas root crops were more common on loamy than sandy sites. However, together these crops accounted for only 7.5% of the site years across all sites.

Ploughing was frequent on both sandy and loamy soils and may occur more than once per year. Between 2009 and 2019, the median number of ploughing events was 7 years for sandy soils and 8 for loamy soils (Figure 5).

The median number of years with cover crops was 1 for both sandy and loamy soils in the 10-year period, and the median number of years with straw incorporation was 2 for sandy soils and 3 for loamy soils (Figure 5).

Pig manure was the most common source of organic fertilizer in the 10-year period for both sand (median, 3.4 years) and loam (2.7 years), followed by cattle manure (median, 2.0 years and 1.2 years, respectively) (Figure 6). Sandy soils received organic fertilizers more frequently than loamy soil; for sandy soils the median frequency of "No addition" was 2.7 years, while it was 4.5 years for loamy soils.

Across all sites, clay content and the crop types and management parameters are generally highly correlated with each other as well as geographic longitude. In particular, autumn-sown and perennial crops correlate often with other management parameters (Figure 7). There are fewer and weaker correlations between crop types and clay content as well as longitude when the sites are divided into sandy and loamy soils, however, the correlations between the crops and the management parameters remain (Figure 7).

3.2.2 | Management effects

For the topsoil (0–25 cm), the average SOC stock (2009–2019) was a statistically significant parameter for the change in SOC stock for both the whole data set and for the sandy and loamy subsets, with an overall negative effect (Table 3, Figure 8). The effect was more negative for sandy than for loamy soils. Thus, sites with greater SOC stocks in 2009 were more likely to have lost C in the topsoil between 2009 and 2019, and the trend was more pronounced for sandy soils. The clay content was not a statistically significant parameter for explaining SOC changes for either soil layer.

Perennial crops showed a significant positive effect on the topsoil SOC stock for the whole data set as well as for the loamy subset, but not for the sandy subset nor for the subsoil (Table 3, Figure 8). Autumn-sown crops did not show a statistically significant effect for either soil layer or soil group, while spring-sown crops only had a

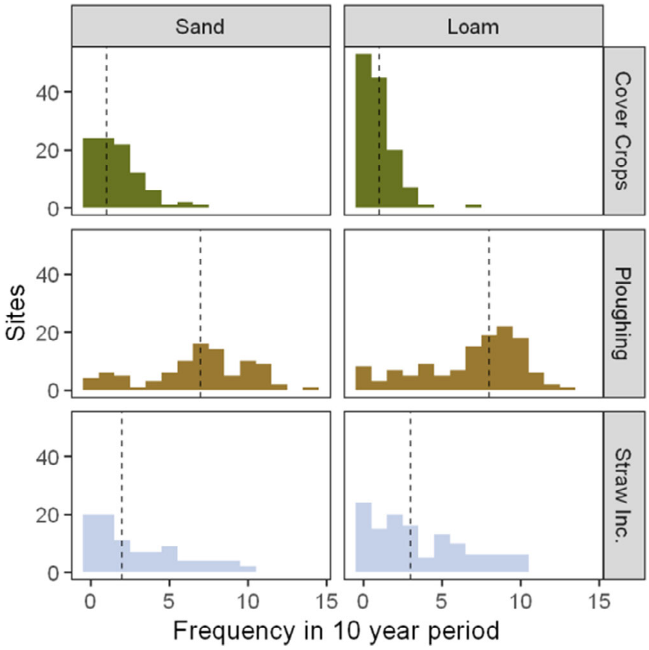

FIGURE 5 Number of sites in the NSG with the given frequency of years with cover crops (green), number of ploughing events (brown), and years with straw incorporation (blue) between 2009 and 2019 for sandy and loamy soils. The vertical line is the median value.

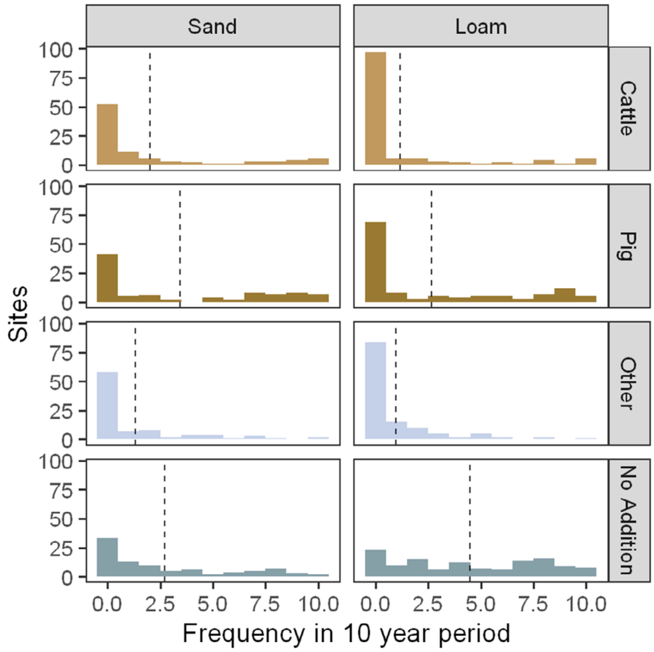

FIGURE 6 Number of sites with the given frequency of application of organic fertilizer at the NSG sites during 2009–2019 for sandy and loamy soils. The vertical line is the mean number of applications of organic fertilizer. Cattle (light brown) is the number of years with the application of cattle manure from both meat and dairy production; Pig (dark brown) refers to the number of years with applications of manure from pigs; Other (light blue) includes all other organic fertilizer, including manure from other animals and mixed animal origins, as well as organic waste from industrial production. No Addition (dark blue) represents the total number of years where no organic fertilizer was applied.

significant negative effect for the combined group in the subsoil.

Straw incorporation had a statistically significant positive effect on SOC stock change in the topsoil for both the sandy and loamy subsets as well as for the full data set. The effect was greater for loamy than for sandy soils (Table 3, Figure 8).

In the subsoil, both straw incorporation and ploughing had significant positive effects on the whole data set. However, for the sandy subset, only ploughing showed a significant effect, while only straw incorporation showed a significant positive effect for the loamy soils.

The R^2 values of the models were relatively small for the whole dataset (Table 3). For the topsoil, the model had an R^2 value of 0.46 for the sandy soils, but only 0.21 for the loamy soils. In the subsoil, the R^2 values were 0.20 and 0.22 for sandy and loamy soils, respectively.

3.3 | Changes in SOC stock between 1986 and 2019

Data on SOC contents in fine soil (<2 mm) from the NSG sites were available from national surveys in 1986 and 1997 in addition to the two surveys reported in the present study. Using sites included in all four surveys ($n = 229$), four snapshots of the SOC stock of the same NSG sites at different points in time were produced (Figure 9).

There is relatively little change in the mean SOC stock between 1986 and 2019 across the soil types (Figure 9). However, the shape of the distributions changed over time and became less positively skewed for sandy and all soils, while the distribution of SOC stock in loamy soils became more skewed. A reduction in the skewness of the distributions means that the distribution of the SOC stock estimates becomes more even; either through a loss of extreme values at one end of the spectrum or an addition of extreme values at the other end of the spectrum. In this case, the extremely high SOC stocks disappeared over time, which reduces skewness.

4 | DISCUSSION

4.1 | Changes in SOC stock

Soil characteristics influence the SOC stock as well as changes in SOC (Kögel-Knabner & Amelung, 2021; Wiesmeier et al., 2019). For example, soils low in SOC

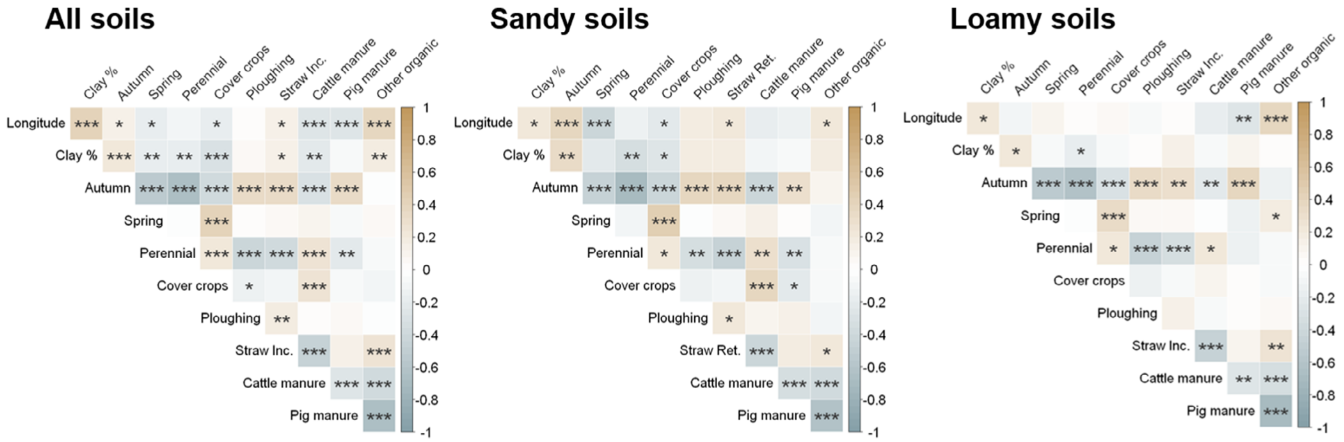

FIGURE 7 Correlogram of the Spearman's correlation coefficient for the crop categories and management activities for all sites ($n = 216$), and separately for sandy soils ($n = 90$) and loamy soils ($n = 126$). Longitude is the longitudinal coordinate of the site, Autumn is the number of years with autumn-sown crops, Spring is the number of years with spring-sown crops, Perennial is the number of years with perennial crops, Cover Crops is the number of years with cover crops, Ploughing is a number of ploughing or tillage events, Straw Inc. is the number of years where straw is either left on the surface or incorporated into the soil through ploughing or tillage, Cattle manure, Pig manure and Other organic are the number of individual applications of manure from cattle, pigs and from other sources. Warm colours signify a positive correlation, while cooler colours signify a negative correlation. Darker colours signify stronger correlations. The asterisks signify different levels of significance; *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

are unlikely to lose SOC, illustrating that initial SOC stock affects the potential change. The mean SOC stock between 2009 and 2019 was a significant predictor of the change in SOC stock during this period for both the sandy and loamy topsoils (Table 3, Figure 8); the greater the mean SOC stock, the greater the risk of loss.

The sandy soils contained the greatest SOC stock in both the topsoil and subsoil (Figure 2). Many of the coarse sandy soils in Denmark were converted from heathland to cropland between 1850 and 1900. Much of the pre-cultivation SOC in these soils is very resistant to decomposition, and despite many decades under cultivation, they still contain a large stock of SOC (Thomsen et al., 2008; Vos et al., 2019).

There is no immediate explanation for the opposing trends in SOC stock changes in the topsoil and subsoil. In general, the mechanisms regulating subsoil SOC dynamics remain unclear and call for further studies (Button et al., 2022; Rumpel & Kögel-Knabner, 2011). An increase in subsoil SOC may reflect multiple sources; (1) deep roots and their exudates, (2) leaching of dissolved organic C, (3) downwards movement due to bioturbation, and (4) physical movement, for example, due to deeper ploughing (Button et al., 2022). Organic C deposited at greater depths may have longer mean residence time and be older than C deposited in the topsoil since microbial activity and mineralization tend to decrease with soil depth (Button et al., 2022; Rumpel & Kögel-Knabner, 2011; Shi et al., 2020). Assuming that the increases in subsoil SOC stock are primarily due to the movement of SOC from the topsoil to the subsoil, the increase in subsoil SOC stock may also in part explain the loss of SOC in the topsoil. Therefore, not all of the organic C lost from the topsoil may have been emitted as CO_2 to the atmosphere. Altogether, the different changes in topsoil and subsoil SOC illustrate the importance of including subsoil layers when monitoring SOC stock dynamics.

Overall, the SOC stock at the 229 sites, sampled four times between 1986 and 2019, appears to be relatively stable over this 33-year period (Figure 9). Although the mean SOC stock of agricultural soils in Denmark seems to vary within a relatively small range, the SOC dynamics at individual sites may vary substantially over time. Extrapolating trends from mean values across soil categories or regions to individual sites within these groupings may not be valid. Clearly, site-specific measurements of SOC stock are needed to reflect SOC stock dynamics at field-scale, for example, for use in carbon credit schemes.

4.2 | Effect of management, crops and soil parameters on SOC stock changes

The linear model (Table 3) with relatively low R^2-values (0.16–0.46) was limited by the strong correlations between the independent variables, which leads to high variance inflation, and the results of the model should therefore be interpreted cautiously (Miles, 2014; O'brien, 2007). Whereas the significance of the effect of parameters can be compared, as can the direction and

TABLE 3 Effects on mean soil organic carbon (SOC) stock change between 2009 and 2019 of clay content (%), mean SOC (Mg C ha^{-1}), the three crop categories, that is, autumn-sown crops, spring-sown crops, perennial crops (years), and the three management activities, that is, cover crops (years), straw incorporation (Straw inc., years), ploughing (events), and application of cattle and pig manure (number of applications).

0–25 cm	All sites (n = 216) R^2 = 0.29		Sand (n = 90) R^2 = 0.46		Loam (n = 126) R^2 = 0.21	
Variable	**Est.**	***P***	**Est.**	***P***	**Est.**	***P***
Clay %	0.11	0.129	0.35	0.116	−0.06	0.652
Mean SOC	**−0.12**	**0.000**	**−0.15**	**0.000**	**−0.10**	**0.001**
Autumn	0.24	0.279	−0.09	0.769	*0.61*	*0.090*
Spring	0.14	0.572	0.18	0.622	0.29	0.404
Perennial	**0.58**	**0.003**	0.28	0.322	**0.92**	**0.002**
Cover crops	−0.15	0.612	0.00	0.999	−0.14	0.775
Straw inc.	**0.52**	**0.000**	**0.46**	**0.024**	**0.53**	**0.003**
Ploughing	−0.10	0.446	0.11	0.573	−0.21	0.234
Cattle	0.21	0.150	0.09	0.686	0.29	0.167
Pig	0.03	0.776	0.11	0.487	−0.05	0.726
25–50 cm	**All sites (n = 216) R^2 = 0.16**		**Sand (n = 90) R^2 = 0.20**		**Loam (n = 126) R^2 = 0.22**	
Variable	**Est.**	***P***	**Est.**	***P***	**Est.**	***P***
Clay %	0.04	0.614	0.39	0.159	−0.12	0.389
Mean SOC	−0.01	0.752	−0.08	0.174	0.04	0.348
Autumn	−0.13	0.665	−0.40	0.444	−0.02	0.965
Spring	*−0.55*	*0.087*	−0.42	0.445	−0.50	0.218
Perennial	0.08	0.741	−0.12	0.778	0.29	0.385
Cover crops	0.35	0.404	0.21	0.741	0.66	0.275
Straw inc.	**0.43**	**0.019**	0.24	0.465	**0.61**	**0.006**
Ploughing	**0.37**	**0.036**	**0.73**	**0.020**	0.20	0.351
Cattle	0.06	0.767	−0.07	0.848	0.11	0.662
Pig	−0.11	0.443	−0.23	0.339	−0.03	0.887

Note: Effects were derived for a linear model for the topsoil (0–25 cm) and subsoil (25–50 cm). The unit of the estimate (Est.) is Mg C ha^{-1} per unit of the variable. The results are presented for all 216 sites together, as well as the soil groups "Sand" and "Loam". Estimates with $P < 0.05$ are shown in bold, while estimates with $P < 0.1$ are shown in italics. The coefficient of determination (R^2) is given for each model.

size of the effects, care should be taken when extrapolating the modelled effects of management parameters observed in the present study. This is because the dataset is unbalanced as some management practices and crops are more likely to co-occur or not occur simultaneously (Figure 7). Effects of individual management parameters may not be additive nor reflect the effect of individual parameters in isolation or when arbitrarily combined, as interactions between management parameters and soil parameters were not included in the model.

Furthermore, the SOC stocks of sites included in the soil survey may not be in equilibrium and may have been subject to historic changes in management introducing long-lasting changes in SOC stock. The effect of the management parameters therefore reflects the variation of these parameters on soils at varying initial SOC stocks and paths towards SOC equilibrium, which itself may shift when the management practices are changed (Jensen et al., 2022). Additionally, the effect of management practices before 2009 may still have impacts on the SOC stock dynamics observed between 2009 and 2019, for example, land-use change (Christensen et al., 2022; Hu et al., 2019).

4.3 | Consequences and reduction of correlations in management parameters

The traits of certain crops and the types of management activities inherently prevent certain combinations, for example, fields with autumn-sown crops cannot have a cover crop, and fields with perennial crops may not be ploughed. These crop types and management activities were therefore strongly negatively correlated (Figure 7). Similarly, the frequency of the most common crop types is significantly negatively correlated, as it is not possible to have many years (>50%) of two different crop types (Figure 7).

Significant positive correlations between certain management activities were also expected; straw incorporation usually happens in combination with ploughing, and spring-sown crops and cover crops were expected to be positively correlated as Danish legislation calls for a plant cover during the autumn and winter periods to reduce nitrate leaching (Aronsson et al., 2016; Landbrugsstyrelsen, 2022). Similarly, the occurrence of perennial crops was positively correlated with cover crops as perennial grassland was usually established as an undersown cover crop.

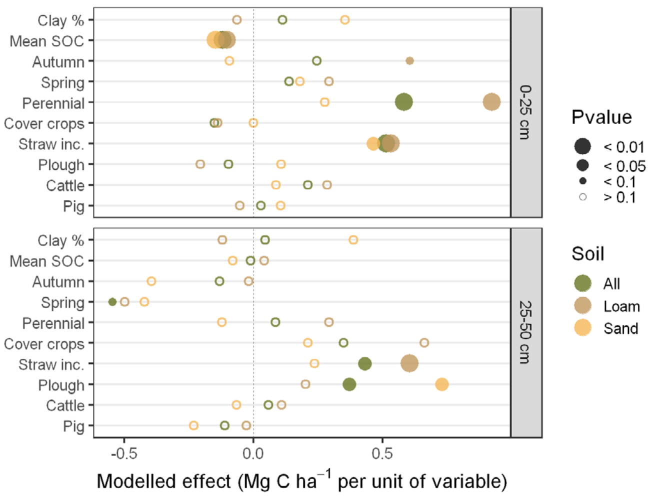

FIGURE 8 Modelled effect of the soil and management parameters on SOC change between 2009 and 2019 for the topsoil (0–25 cm) and subsoil (25–50 cm) and all soil groups (green), loamy soils (brown) and sandy soils (yellow). The *P*-value is indicated by the size of the points; the larger the point, the smaller the *P*-value. Effects with $P > 0.1$ are shown with a white centre. The units of the modelled effect are Mg C ha^{-1} per unit of the variable, for example, for autumn-sown crops, the unit of the modelled effect is Mg C ha^{-1} per year with the autumn-sown crop.

Lastly, the longitudinal coordinates of the sites correlated strongly with both the clay content as well as multiple management parameters (Figure 7). Thus, there was a spatial division of the farm types and associated farming practices that correlates strongly with the distribution of soil types. Farmers are influenced by their local conditions, including climate and soil texture, in their choice of crops and farm management as well as the economic prospects of the crops and costs of management. Thus, the correlation between clay content and management choice by the farmer is expected but nonetheless results in highly correlated management and soil data.

The strong correlations between independent variables make it difficult to distinguish the effect of a single management parameter from the correlated management parameters (e.g., a significant effect of spring-sown crops may be due to the crop itself, an associated farm management practice like ploughing, or the absence of a different crop). Combined with the relatively low R^2-vaues for the fitted model, it is not recommended to draw conclusions based on the numeric values or significance of the model itself. The relationships between soil type, SOC stock, crop type, management and the corresponding change in SOC stock are too complex to capture individual effects of farm management practices with a statistical analysis of the data derived from the NSG.

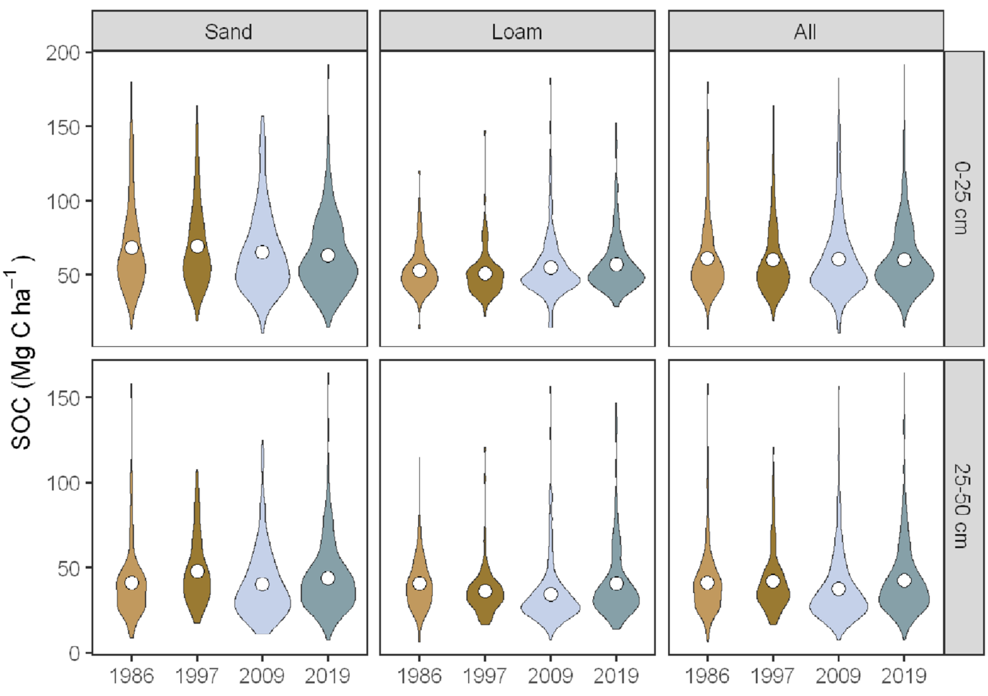

FIGURE 9 Violin plot of the distribution of soil organic carbon (SOC) stocks (Mg C ha^{-1}) in 1986, 1997, 2009, and 2019 for the NSG sites present in all four surveys ($n = 229$) for the topsoil (0–25 cm) and subsoil (25–50 cm) for sandy ($n = 117$) and loamy ($n = 112$) soils. The white circle indicates the mean SOC stock.

One way to circumvent the statistical challenge of strong parameter correlations could be to use a subset of the data, where the correlations may be less strong, for example, dividing the sites into sandy and loamy soils. This may reduce correlations between clay content, crops and management practices (Figure 7), but does not affect inherent negative correlations formed by mutually exclusive crop and management combinations. Accounting for those correlations could potentially be done by categorizing sites by predominant farming practice (e.g., autumn-sown crops, cereal crops, manure origin, etc.) and then assess the effect of the crops, management and soil parameters within the more specific categories and not including the group-defining parameters in the model (e.g., predominant crop). However, with the present NSG, such a specific grouping would either result in a very low number of sites within each group, thus limiting the validity of the statistical analysis, or result in broad categories with a small reduction in the strength of the correlations.

A division by soil characteristics was used by Drexler et al. (2022) to develop benchmarks of SOC stocks in agricultural soils in Germany, and Knotters et al. (2022) divided their inventory by geology and by management practice when calculating the changes in SOC stock for the Netherlands. Dividing the Danish sites into sandy and loamy soils reduced the correlations between the model parameters somewhat (Figure 7); however, in a few cases, the variance inflation factor increased (Table S1). Additionally, the model results varied only slightly between the two subsets (Table 2, Figure 8), suggesting that clay content is not a useful criterion for the division of soils in the NSG when analysing the effects of farm management factors.

4.4 | Implications for monitoring, reporting and verification of SOC stocks

Monitoring, reporting, and verification of SOC stocks to support national inventories of C balances require high-quality data on changes in SOC stocks, with sources of uncertainty and errors being reported (Oldfield et al., 2022; Smith et al., 2020). Our results demonstrate that several aspects should be considered in this context, including frequency of sampling, depth intervals of the sampling, data on bulk density and rock fragments (Harbo et al., 2022), as well as linkages to farm management.

An inherent uncertainty related to repeated samplings in national SOC monitoring networks is regression to the mean (Callesen et al., 2015; Slessarev et al., 2023). One consequence of regression to the mean may be that the observed changes in SOC stock over time may be artefacts of the repeated sampling scheme. To reduce the potential effect of regression on the mean in the present study, observations with decadal changes >20 Mg C ha^{-1} were excluded from the analyses of the changes in SOC stock between 2009 and 2019. The pooling of 16 soil cores (as performed in the present study) also reduced the risk of an unrepresentative sample, although the field-scale variation in SOC of individual sampling sites remains unknown.

Although measurable changes in SOC stock occur slowly at decadal or centurial pace (Post & Kwon, 2000; Smith, 2004; Smith et al., 2008), more frequent sampling would allow for a better estimate not only of the SOC stock but also of the errors associated with the sampling itself. Nerger et al. (2020) suggested that yearly sampling is optimal for reducing the noise of inter-year variation and detecting any overall direction of change in SOC stocks. More frequent sampling and measurement of SOC stock may reduce the effects of regression on the mean for SOC stock inventories of all scales, as the mathematical issues are not exclusive to large-scale inventories or monitoring networks. In contrast, Saby et al. (2008) concluded that sampling once every 10 years is sufficient for soil-monitoring networks, as it allows for the detection of overall changes in SOC stocks, considering the slow rate of change. Despite less frequent samplings being significantly cheaper, the inter-annual variability remains an unknown factor in determining how representative the sampled years are for the entire period between samplings. A potential compromise would be more frequent samplings of a representative subset of the sampling sites to quantify inter-annual variability in addition to a less frequent sampling of all sites to track the overall trends in SOC stock development.

Plot-scale variation and time of year of sampling may affect the observed difference in SOC stock. Poeplau et al. (2022) showed that the sampling and resampling strategy significantly affects the variability in SOC stock estimates, and suggested that multiple samples should be collected to reduce the variability in SOC stock estimates for individual sites. Similarly, Leinweber et al. (1994) and Wuest (2014) showed that the seasonal variation in SOC as well as bulk density may be relatively high, and could be affected by weather, crop and agricultural management such as tillage. Despite all samplings in the Danish NSG were carried out during winter and autumn, these effects cannot be entirely eliminated and may reduce the representativeness of a single sampling site and year.

From a monitoring or economic viewpoint, soil-monitoring networks may be a less feasible approach to explain the effects of farm management parameters on SOC stocks. Although soil C turnover models rely on a range of assumptions, these may be applied to predict changes in SOC stocks due to soil management at a regional and national level (Taghizadeh-Toosi & Olesen, 2016), providing adequate initialisation of models.

5 | CONCLUSIONS

The present study showed opposing trends for changes in SOC stored in topsoil and subsoil between 2009 and 2019 in Danish agricultural mineral soils. This stresses the importance of including subsoils in soil-monitoring networks.

Measurements in the NSG at four surveys from 1986 to 2019, collectively showed a relatively stable mean SOC stock at the national scale, although there was considerable variability for individual sites. More frequent sampling may give better information about inter-annual variability as well as overall trends in time for individual sites.

The statistical assessment of management effects on SOC stock changes was challenged by the correlations of management practices, crops, and soil types. It was possible to distinguish the effect of individual agricultural management practices on the changes in the SOC stock using a linear model, but often with low R^2 values. We, therefore, conclude that farm management data had statistical limitations in explaining decadal-scale changes in SOC stocks of agricultural mineral soils in Denmark. However, the determination of SOC stocks at fixed sampling points at decadal intervals remains an important piece of information, reflecting the overall development in national SOC storage.

AUTHOR CONTRIBUTIONS

Laura Sofie Harbo: Investigation; writing – original draft; methodology; visualization; writing – review and editing; formal analysis; data curation. **Jørgen E. Olesen:** Conceptualization; writing – review and editing; supervision; funding acquisition; methodology. **Camilla Lemming:** Data curation; resources. **Bent T. Christensen:** Writing – original draft; writing – review and editing. **Lars Elsgaard:** Supervision; writing – review and editing; writing – original draft; conceptualization; methodology.

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CONFLICT OF INTEREST STATEMENT

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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