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Importance of sampling frequency for the observed dynamics of SOC content in the Danish long-term monitoring network

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ABSTRACT

Monitoring soil organic carbon (SOC) content is crucial for understanding the role of agricultural soils in carbon sequestration and climate change mitigation. However, the influence of sampling frequency on the accuracy of SOC content trends remains an open question. This study investigates the effect of different sampling intervals using soils from the Danish long-term Soil Monitoring Network (SMN), which includes both decadal (every 10–12 years) and more frequent (7–11 times over 30 years) sampling since 1986, where the latter samples were originally collected (and archived) for analysis of soil mineral nitrogen. Our results show that decadal sampling effectively captures long-term SOC content trends, with no significant differences compared to more frequent sampling. Year-to-year variability in SOC content was high, suggesting that short-term fluctuations may mask long-term trends. This variability is reduced when SOC content trends are analysed over multi-year periods. To balance resource limitations with the need for temporal resolution, we suggest that a 3–5 year sampling scheme could be implemented, where a subset of SMN sites is sampled each year. This approach would provide finer temporal detail without the cost and effort of annual monitoring, while maintaining the ability to detect meaningful trends in SOC content dynamics. From an operational perspective, a rotational or rolling sampling strategy where only a fraction of sites (e.g., 20–30 %) are sampled each year such that all sites are eventually sampled in the monitoring period, would also help to maintain continuity of field expertise and laboratory capacity, ensuring consistent data quality over time.

1. Introduction

The incorporation of organic carbon (C) into agricultural soils and its release as CO_2 through respiration are key processes shaping climate change trajectories with the balance of the processes reflected in the dynamics of soil organic carbon (SOC) stocks (Davidson and Janssens, 2006; Jungkunst et al., 2022). To mitigate rising atmospheric CO_2 levels, initiatives to increase SOC stocks are gaining momentum from farmers to policy makers as part of an economy based on carbon credits and subsidies for climate-smart agriculture (Amelung et al., 2020; Rumpel et al., 2020; Black et al., 2022). For Europe, the EU Soil Strategy 2030 aims to increase SOC stocks and contribute to the goal of land-based climate neutrality by 2035 and a climate neutral Europe by 2050 (European Commission, 2021, 2023). The strategy outlines the intention to establish a legal framework for certification of CO_2 removal, thereby encouraging and financially incentivising farmers to adopt management practices that are expected to result in SOC sequestration. In line with these initiatives, scientific research focuses on management options that have the potential to increase SOC stocks (e.g., Chenu et al., 2019; Don et al., 2023; Gocke et al., 2023), but also on how such SOC changes can be monitored, reported and verified (FAO, 2020; Smith et al., 2020; Oldfield et al., 2022; Dupla et al., 2024).

Soil sampling to determine bulk density and direct analysis of organic C by dry combustion methods remain the most accurate way to quantify SOC stocks and changes therein, but the procedures are laborious and interpretations can be complex (Goidts et al., 2009; Jensen et al., 2018; Rollett and Williams, 2020). The main challenges are that SOC content and stock are spatially variable, both vertically and horizontally, even at centimetre scales in the field (Heinze et al., 2018; Bradford et al., 2023), and annual SOC stock changes are small compared to existing stocks (Mobley et al., 2019), making it difficult to detect such changes (Bentley et al., 2023). Furthermore, the assessment

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of trends in SOC content and stock may be challenged by short-term variability, which is poorly understood, but may be influenced by seasonal changes in rainfall and organic inputs (Leinweber et al., 1994; Wuest, 2014; Gubler et al., 2019).

Long-term soil monitoring networks (SMNs) provide a unique opportunity to document changes in SOC stocks over time and to relate these observations to management practices, where such information is available (Taghizadeh-Toosi et al., 2014; Gubler et al., 2019; Poeplau et al., 2020). Long-term SMNs exist in several countries, but typically with different designs and monitoring strategies (Froger et al., 2024; Meurer et al., 2024). A key parameter in the design and operation of SMNs is the frequency of resampling to adequately document SOC stock trends, with arguments presented for both annual and decadal sampling strategies (Saby et al., 2008; Desaules, 2012; Nerger et al., 2020). Annual sample collection allows for detailed analysis of both short-term variability and long-term trends but is often prohibitively resource-intensive. In contrast, sample collection at decadal intervals results in fewer data points over time for statistical analysis, limiting the ability to assess shorter-term changes, and potentially increasing the influence of outliers or extreme observations due to fewer overall observations. However, due to the high labour and analytical costs, SOC datasets with frequent sampling within SMNs are rare, and optimizing sampling frequency remains a critical area for future research to ensure robust documentation of SOC content and stock trends. Notably, it is unclear if the trends from decadal soil sampling align with those observed from more frequent sampling, further emphasizing the need for comparative studies.

In Denmark, a regular sampling grid of 7 km × 7 km (the National Square Grid, NSG), was established in 1986 and soil samples for SOC content and stock analysis have been collected from agricultural sites in the NSG at intervals of 10–12 years, here referred to as decadal sampling, DS (Harbo et al., 2023a). In the intervening years, a varying subset of the NSG sites have been sampled annually for quantification of soil mineral nitrogen (N_{min}) to optimize the N fertilization in Danish agricultural soils, which was the original purpose of the NSG (Østergaard, 1989). Based on SOC content analyses of archived soils from sites with up to eleven N_{min} samplings since 1986, the objectives of this study were (i) to compare the SOC content and changes over time derived from DS and frequent sampling (FS) strategies in the Danish long-term SMN, (ii) to assess the range of trends in SOC content derived from FS data by a simulation approach, and (iii) to evaluate the importance of more frequent sampling in the Danish SMN.

2. Materials and methods

2.1. Soil samples and SOC analyses

Soil sampling for decadal SOC analysis in the NSG was carried out in 1986, 1996/97, 2008/09 and 2018/19, i.e., over a period of 34 years, on 590, 336, 507 and 406 sites, respectively, with 229 sites being sampled during all four campaigns. The procedures and results of the sampling campaigns have been successively reported in detail by Heidmann et al. (2001, 2002), Taghizadeh-Toosi et al. (2014) and Harbo et al. (2022, 2023a). Briefly, each sampling campaign was based on a strategy in which 16 individual soil cores (1 cm, internal diameter) were collected from an area of 50 m × 50 m at each of the NSG sites and pooled into one soil sample per 25-cm depth interval down to 50 or 100 cm. Soils were air-dried and sieved (2 mm) prior to analysis for total carbon (TC) by high-temperature combustion, while inorganic carbon (IC), if detected by a HCl effervescence test, was quantified by a titration method, to allow calculation of organic carbon (OC) as the difference between TC and IC (Taghizadeh-Toosi et al., 2014). Available decadal OC data from 14 of the NSG sites were included in the present study to compare to the results from OC analyses that were performed on the basis of archived N_{min} soil samples (see below). Site-specific bulk density was not measured in the NSG until the 2019 sampling campaign, and thus only changes in SOC content is assessed in this study.

Annual sampling campaigns for N_{min} analysis in the NSG have been carried out since 1987 by SEGES (previously a part of the Danish Agricultural Advisory Service) on a varying subset of approximately 100–300 of sites per year. Samples were usually taken in February (winter) to ensure an estimate of soil mineral N before the growing season. The subset of sites to be sampled was selected each year based on a combination of criteria, such as previous main crop, soil texture, absence of fertilization since the previous July, and absence of cover crops during sampling season, to obtain a representative result of residual mineral N content in Danish agricultural soils. To avoid geographical clustering, the sites were previously selected across administrative regions weighted by area. About half of the sites were sandy soils (S) with low clay content (<100 g clay kg^{-1} soil), while the other half were loamy soils (L) with 100–250 g clay kg^{-1} soil. Samples were typically taken to a depth of 1 m using the same procedure as for the DS sampling campaigns, i.e., with 16 individual soil cores at each NSG site that were pooled into a composite sample for each 25 cm layer for analysis. Bulk density was also not measured at the N_{min} sampling campaigns.

Archived air-dried soil samples from the 0–25 cm (topsoil) and 25–50 cm (subsoil) layers were retrieved for SOC analysis in 2023. Since a different subset of NSG sites is selected for N_{min} analysis each year, the frequency of sampling for a given site varies. We looked for sites with the most frequent co-representation of archived topsoil and subsoil, and representing both sandy and loamy soils. Fourteen sites were identified that had been included in 7–11 (median 10) N_{min} sampling campaigns since 1986, representing seven sandy and seven loamy soils (Table 1, Fig. 1A). These are the sites referred to as frequent sampling (FS) sites.

Typically, 50–250 g of archived soil was available for each site and depth; this soil was carefully mixed using a clean spoon and 10–20 g was ground in a mortar to eliminate any aggregates formed during storage. Approximately 1 g of dry soil was analysed for OC content using a Vario Max cube CN analyzer (Elementar Analysensysteme GmbH, Germany). The CN analyzer was operated at a combustion temperature of 950 °C and calibration was performed using standards of aspartic acid as previously described in Taghizadeh-Toosi et al. (2014).

While 14 sites are relatively few to represent an entire country, the sites were selected for frequent sampling as they are representative of the range of soil texture, OC content and agricultural management practices for the soils under agricultural management in Denmark (Fig. 1B).

In the 10-year period between 2009 and 2019 (i.e., the two most recent national sampling campaigns), the most common main crops of the FS sites were winter-sown crops (cereals and rapeseed; 68.5 %) followed by spring-sown cereals (16.7 %). The remaining crops were maize (2.8 %), root crops (e.g., potatoes, 2.8 %) and grass (0.9 %). Cover crops were included in 10 % of the years; this is less frequent than common practice in Denmark, but reflects that sites were only eligible for the N_{min} sampling scheme if no cover crops were present in the given year, as to more accurately reflect the residual N content in the soil. In the same time period (2009–2019), cereals, maize and root crops were grown on average on 56.3 %, 7.2 % and 3.3 % of the agricultural area in Denmark, respectively; the majority of the remaining area was sown with grass, either for fodder production or utilized as ley (Danmarks Statistik, 2025). Thus, in relation to common agricultural practice in Denmark the FS sampling sites (as well as the DS sites in the NSG) did not represent permanent grasslands, but mainly arable land.

The mean annual precipitation in Denmark was 782 mm in the 2011–2020 period, while the mean annual temperature was 9.1 °C in the same period (DMI, 2021a, 2021b).

2.2. Data analysis and statistics

Long-term trends in SOC content from the FS observations were derived from linear regression models fitted to the 7–11 observations for

Table 1
Clay content (%), bulk density (g cm^{-3}), rock fragment content (vol%), mean organic C content (g kg^{-1}) and corresponding standard deviation (sd) at the 14 sites from the National Square Grid (NSG) with frequent sampling (FS). Clay content is given for topsoil (0–25 cm) only, as the sites in the NSG are classified by topsoil texture. Mean organic C content is based on all FS observations. The number of observations may vary between topsoil and subsoil (25–50 cm) due to, e.g., insufficient amounts of dried soil in the archived samples. S1-S7, sandy soils; L1-L7 clayey soils. na, not available.

Topsoil	unit	S1	S2	S3	S4	S5	S6	S7	L1	L2	L3	L4	L5	L6	L7
Observations	–	7	10	10	11	9	10	9	10	9	9	11	8	10	10
Clay content	g kg^{-1}	30	39	62	76	77	88	93	102	102	159	172	196	223	236
Bulk density	g cm^{-3}	1.45	1.27	na	na	1.43	na	1.15	1.45	1.34	1.44	1.69	1.65	1.44	1.23
Rock fragments	vol%	0.8	0.7	na	na	1.1	na	2.2	7.1	3.8	1.8	1.7	1.5	1.7	2.3
Mean OC	g kg^{-1}	8.5	20.0	13.0	14.5	20.4	12.0	19.2	12.2	16.4	11.7	10.6	12.1	9.7	17.7
OC sd	g kg^{-1}	0.7	3.6	0.8	0.9	2.5	0.5	1.2	1.5	1.6	1.3	1.0	0.5	1.5	1.6
Subsoil															
Observations	–	7	10	11	11	9	10	8	10	9	9	11	8	11	10
Bulk density	g cm^{-3}	1.50	1.18	na	na	1.35	na	1.27	1.51	1.50	1.67	1.74	1.67	1.17	1.49
Rock fragments	vol%	5.0	1.1	na	na	1.3	na	4.1	6.8	3.0	1.6	3.2	2.3	1.7	0.7
Mean OC	g kg^{-1}	4.9	15.1	7.9	10.5	8.3	6.7	12.1	8.0	9.9	6.2	5.9	8.2	5.5	8.8
OC sd	g kg^{-1}	0.8	2.3	1.8	1.5	2.3	1.1	1.2	2.2	1.8	1.2	1.4	1.4	2.1	2.0

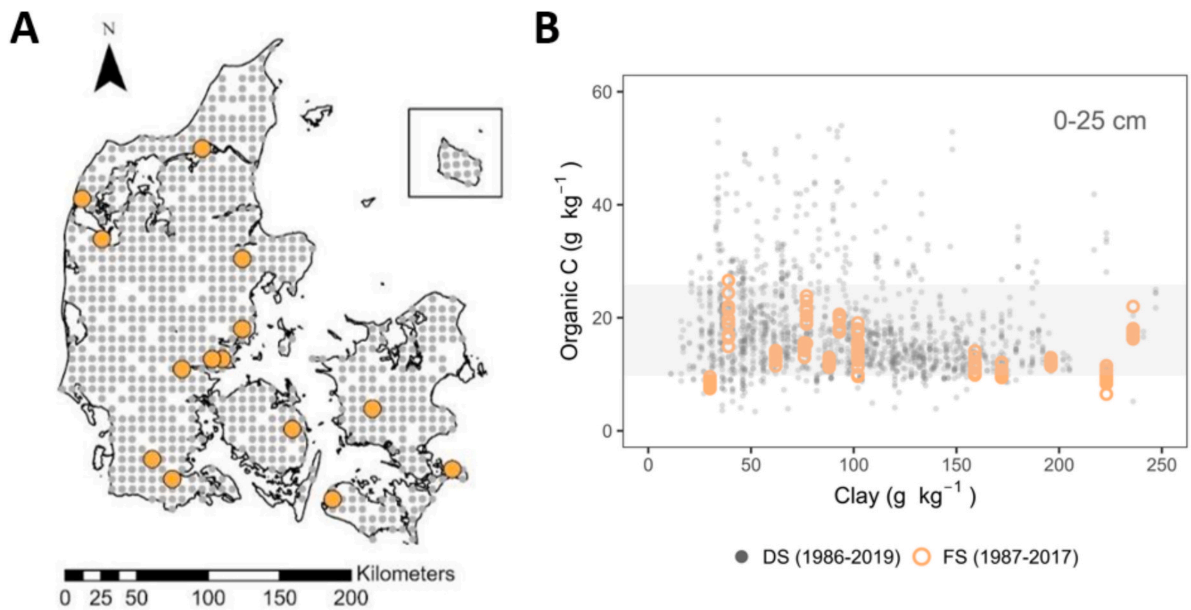

Fig. 1. A) Map of Denmark showing all sites in the National Square Grid, NSG (grey symbols) and the 14 frequently sampled (FS) agricultural sites included in the present study (orange symbols). B) Plot of the topsoil organic C content (g kg^{-1}) versus clay content (g kg^{-1}) of all sites in the NSG included in the decadal sampling (DS) campaigns (grey circles) and the FS campaigns used in this study (orange rings). The grey area indicates the mean organic C content ±1 standard deviation.

the individual NSG site-depth data. These trends were compared to those derived from the DS sampling campaigns with maximally four observations during 1986–2019 (Harbo et al., 2023a).

Short-term changes in SOC content were analysed using the FS dataset by calculating the rate of change in SOC content per year (g C kg^{-1} $year^{-1}$) for each pair of consecutive observations for each site-depth. The rate of change was calculated using Eq. 1:

$$Rate\ of\ change = \frac{SOC_j - SOC_i}{Y_j - Y_i} \quad (1)$$

where SOC_i is the SOC content (g C kg^{-1}) at a given observation time (Y_i) and SOC_j is the SOC content at the next consecutive observation time (Y_j) for the given site-depth. The time interval between Y_i and Y_j, varied between 1 and 16 years (median 1.5 years).

The FS observations were used to further test the range of rates of SOC content change that could emerge from samples taken at intervals of at least 3 years as compared to decadal intervals (DS). An algorithm was developed to select all possible sets of at least 4 observations per site-depth from the FS dataset with a minimum interval of 3 years between consecutive samples (script available on Zenodo; https://doi.org/10.5281/zenodo.14637522). All possible combinations of observations per site-depth that satisfy the condition of minimum 3-year intervals between sampling were analysed individually using a linear regression model, resulting in a rate of change of SOC content (g C kg^{-1} yr^{-1}) for each combination of observations. Combinations of 4–6 observations were typically available given the 3-year minimum interval. Each of these subsets represents a theoretical sampling campaign with more frequent sampling than the established DS procedure.

Another set of combinations was generated by including an upper limit of 10 years between observations, but this severely limited the number of possible combinations, which affected the statistical analyses. The results of this approach were not statistically significant for the majority of the sites where analyses could be performed, and the results are shown in supplementary Fig. S2.

The algorithm and additional data analyses of SOC content and rates of change from the DS and the FS sampling campaigns were performed in R version 4.3.1 (R Core Team, 2023). Statistically significant differences were assessed using ANOVA and linear models ($P < 0.05$).

3. Results

3.1. Long-term SOC changes

Long-term changes in SOC content varied among the 14 sites (Fig. 2); some sites (S1, S6, L5) had relatively stable SOC content, while others showed substantial changes that were either consistent (L1,L2) or inconsistent over time (S2, S5, L6). Thus, there was no uniform pattern of temporal change in SOC content across the 14 sites. The SOC content was lower (mean, 40 %) and more variable in the subsoil than in the topsoil with means of 8.4 and 14.2 g C kg^{-1} and coefficients of variation of 0.38 and 0.28, respectively (Fig. 2).

There was good agreement between the observed SOC content from the DS and FS campaigns, with a few exceptions (Fig. 2 and Supplementary Table S1). The median absolute difference between the DS observations and the nearest FS observation (i.e., within 0–3 years; mean 0.9 years) was 0.60 g C kg^{-1} for the topsoil (10th–90th percentiles, 0.08–1.63 g C kg^{-1}) and 1.13 g C kg^{-1} for the subsoil (10th–90th percentiles, 0.17–2.53 g C kg^{-1}).

3.2. Short-term SOC changes

The rate of change in SOC content between consecutive FS measurements was not significantly different ($P > 0.05$) across data pairs with sampling intervals of 1 to 5 years, and both the mean and median changes were close to zero (Fig. 3, Supplementary Table S2). Similarly, no clear differences were observed when longer time intervals were considered, though the number of sites was typically too small for statistical analysis (Supplementary Table S2). However, the variability in SOC content trends was higher for samples with a short temporal interval (1 year), as indicated by a wider interquartile range, which narrowed as the time interval increased (Fig. 3). This pattern was consistent for both topsoil and subsoil, but with slightly larger interquartile ranges for the subsoil (Fig. 3).

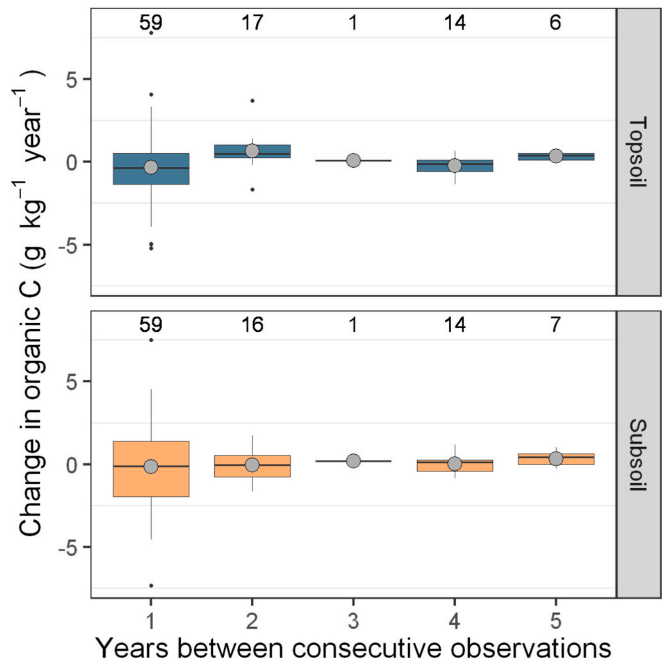

Fig. 3. Trends in SOC content (g C kg^{-1} $year^{-1}$) in topsoil (0–25 cm, blue) and subsoil (25–50 cm, orange) as detected from neighbouring observations in the frequent sampling campaign at intervals of 1–5 years. Boxes show the interquartile range (IQR) with mean (circles) and median (line); numbers indicate the number of observations. Whiskers extend to the lowest and highest values within the 1.5 × IQR range; outliers are shown as dots.

3.3. Simulation of increased sampling frequency

The range of trends in SOC content, as simulated from 4 to 6 measurements drawn from the FS data, differed between the 14 sites (Fig. 4). The interquartile ranges of simulated rates of SOC content change were smaller than 0.2 g C kg^{-1} yr^{-1}, except for site S2, and mostly included the

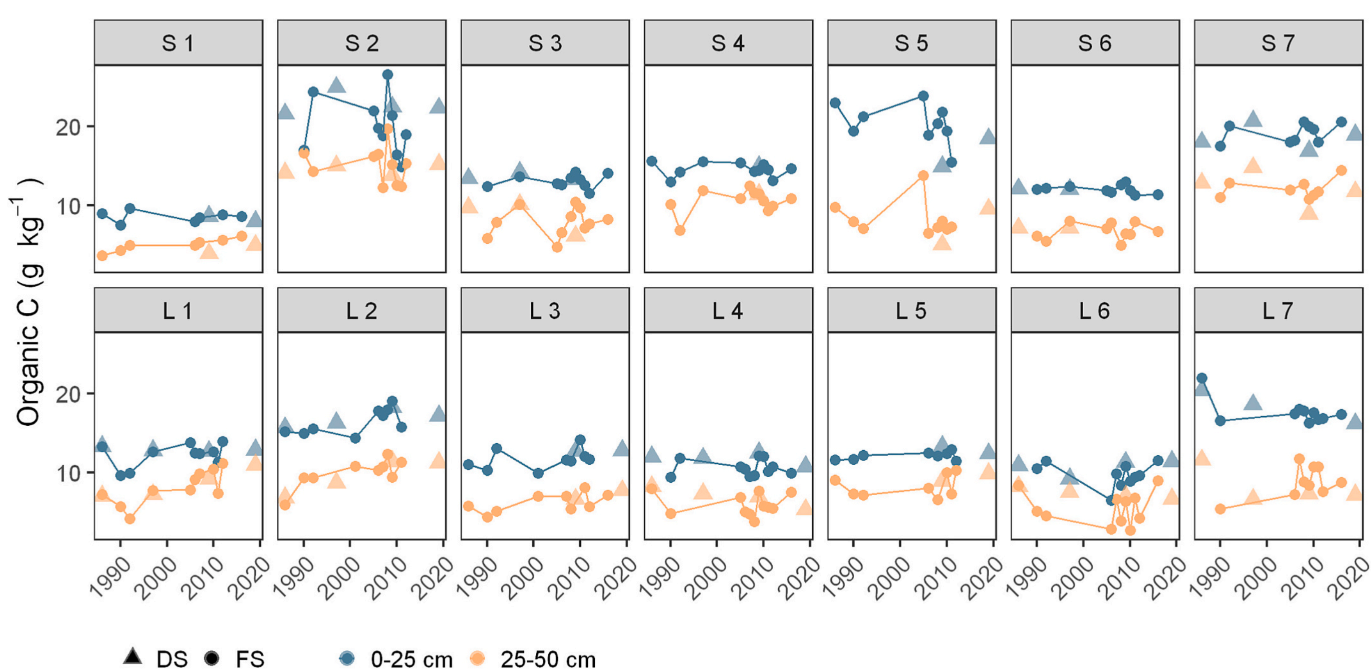

Fig. 2. Temporal dynamics of SOC (g C kg^{-1}) in topsoil (0–25 cm, blue) and subsoil (25–50 cm, orange) at the 14 selected sites in the National Square Grid. Circles represent SOC analyses from the frequent sampling (this study); triangles represent data for decadal sampling as reported by Harbo et al. (2023a). S, sandy soil; L, loamy soil.

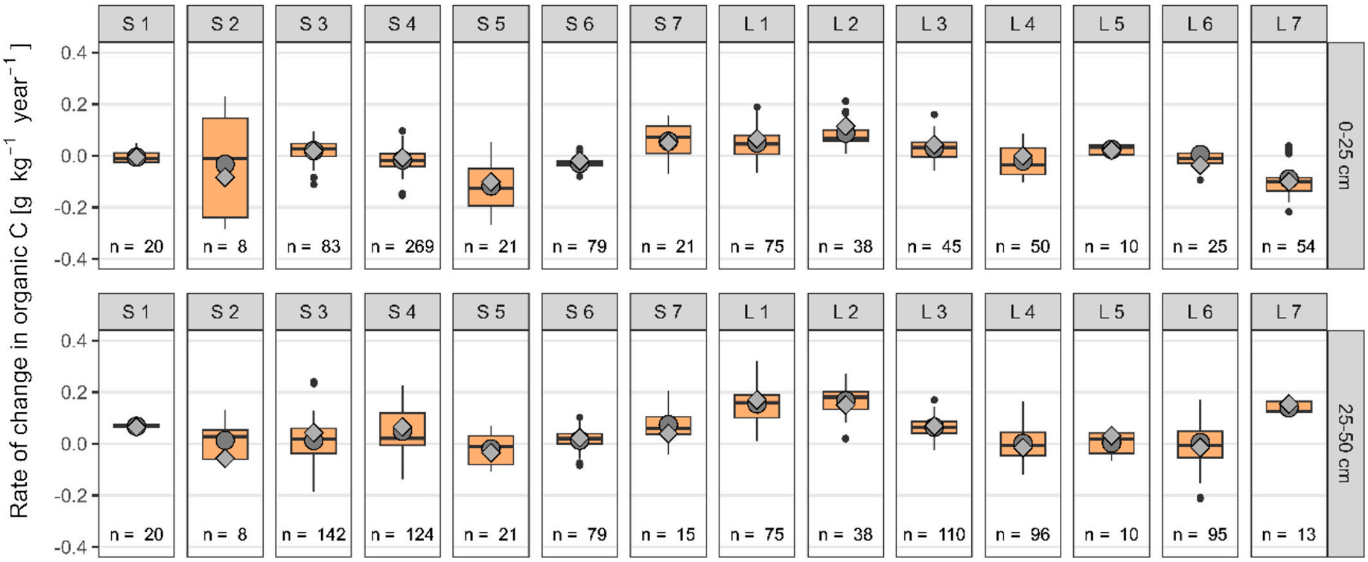

Fig. 4. Simulated trends in SOC content (g C kg^{-1} year^{-1}) for topsoil (0–25 cm; upper panels) and subsoil (25–50 cm; lower panels) at the 14 frequent sampling (FS) sites. The simulations were based on 4–6 observations drawn from the FS data set with a with a minimum interval of 3 years between consecutive samples. Boxes show the interquartile range (IQR) with median (line). Whiskers extend to the lowest and highest values within the 1.5 × IQR range; outliers are shown as dots. The larger grey circles show the mean rate across all 7–11 FS observations, while grey diamonds show the mean rate across the available decadal samples (DS). S, sandy soils; L, loamy soils. The number of possible combinations of observations (n) is given in each panel.

mean of the linear rates derived from all 7–11 FS observations (Fig. 4; circles). The range of rates were typically greater in the subsoil than in the topsoil. In general, the simulated rates (Fig. 4) were small compared to the rates derived from only two consecutive measurements by up to a factor of 10 (Fig. 3).

Overall, the trends in SOC content derived from the DS observations was within the range derived from the FS simulations, but with some exceptions (Fig. 4, e.g., S6 topsoil, L6 topsoil). The mean rate across all FS simulations typically agreed well with the mean rate based on the DS data.

For topsoil, the median of the simulated rates indicated an increasing or consistent SOC content at about half of the sites and decreasing SOC content at the other half (Fig. 4). Similarly, the interquartile range included zero for almost half of the sites, i.e., indicating that both losses and increases in SOC content could be inferred from the FS dataset depending on the specific years selected for the trend analysis. For the subsoil simulations (Fig. 4), no upper interquartile range was below zero, suggesting a more consistent pattern of increasing SOC content than for the topsoil.

4. Discussion

4.1. Comparison of DS and FS observations

Results from the decadal and frequent sampling approaches showed good overall agreement, especially for topsoil samples (Figs. 2, 4). This suggests that the decadal sampling framework captures trends in SOC content reasonably well. The median differences between SOC content in DS and FS samples were relatively small, even when FS measurements are taken within 1–5 years of DS measurements (Supplementary Tables S1 and S2). This supports the idea that, given the natural variability of SOC in soils, changes in SOC over short periods of time may be either negligible or too subtle to be detected with high confidence. Thus, it is challenging to detect short-term SOC changes in agricultural fields, where small shifts may be masked by spatial variability (Don et al., 2007; Poeplau et al., 2022) or sampling error. Indeed, the considerable spatial heterogeneity of soils, even at small scales (Heinze et al., 2018), complicates the ability to detect meaningful temporal trends from short-term observations. The relatively high concordance between FS and DS observations suggests that even with the inherent limitations decadal sampling can adequately capture longer-term SOC trends, which is critical for SMNs aimed at tracking SOC sequestration or SOC losses.

The overall changes in SOC content between consecutive years in the FS dataset were relatively small (-3.2 g C kg^{-1}, corresponding to -2.5 % in topsoil, -1.4 g C kg^{-1}, corresponding to -0.9 % in subsoil; Supplementary Table S2) compared to the potential effects of common agricultural practices on SOC as documented in previous studies (Poeplau and Don, 2015; Mobley et al., 2019; Jensen et al., 2021; Harbo et al., 2023b; Gocke et al., 2023). However, the observed rate of change was greater for year-to-year observations as compared to observations further apart in time, possibly due to dilution of the random error associated with sample collection. Spatial variability is expected to be consistent over time, and the impact of such errors is thus diluted as the time between samples increases. Annual sampling may be too frequent to observe meaningful changes in the SOC content in SMNs where neither replicate samples nor control treatments are available for robust statistical analyses. Furthermore, the variability observed within FS samples indicates sizeable spatial heterogeneity of soils, which makes it challenging to isolate short-term trends from measurement errors and the spatial variability. As a result, annual sampling may not always enhance the detection of SOC trends in large-scale SMNs, especially if replicate measurements are not included for statistical comparisons.

4.2. Simulation of sampling frequency

To simulate more frequent sampling in the Danish SMN, the data from the N_{min} sampling campaigns were analysed using an algorithm to find all possible combinations of observations with a minimum of 3 years between consecutive samples. This minimum interval ensures that very frequent sampling in a short period in the N_{min} campaign are not assumed to be representative for the whole period of more than 30 years. No upper limit was set for the sampling interval, as the use of a maximum of 10 years substantially reduced the number of possible combinations of observations and reduced the statistical power (Supplementary Fig. S2). However, comparisons between SOC trends from combinations with and without this upper limit generally showed no statistically significant difference (Supplementary Fig. S2), so the overall conclusions from both approaches remain consistent.

The simulation results based on the FS dataset suggest that decadal sampling may indeed be sufficient to detect broad trends in SOC changes (Fig. 4). Although more frequent sampling could provide additional data, the simulated SOC change rates derived from 4 to 6 samplings at shorter intervals are broadly consistent with the trends detected by DS. However, variability between sites remains high, particularly in subsoils, which tend to exhibit higher spatial heterogeneity (Poeplau et al., 2022). This is consistent with the observation that changes in subsoil SOC are more gradual and less responsive to short-term variations in management or environmental conditions. Interestingly, the FS data revealed a pattern of topsoil SOC content loss and increasing subsoil SOC content, which aligns with observations from the entire NSG over the most recent decade, from 2008/09 to 2018/19 (Harbo et al., 2023a).

While annual soil sampling could potentially improve the ability to capture short-term fluctuations in SOC, this approach is resource intensive and may not provide substantially better trend-detection than decadal sampling. Analysis of the simulated sampling campaigns suggests that certain years can have a disproportionate impact on calculated SOC change rates, particularly at sites where SOC dynamics are non-linear or inconsistent over time. This was evident at several sites in our study, where the inclusion or exclusion of certain years from the analysis significantly influenced the direction and magnitude of SOC change (Fig. 4). More frequent sampling might mitigate this problem by diluting the influence of a single anomalous year, but the benefit may not justify the additional cost and effort.

The consistent alignment of DS and FS trends at sites with more stable SOC dynamics (e.g., S4, S6, L6) suggests that decadal sampling is sufficient to capture general trends for these sites. The greater variability at other sites, where SOC change is more erratic or non-linear, may justify more frequent monitoring. However, short-term changes in SOC content may not always be relevant for long-term monitoring, as SOC sequestration or loss typically requires sustained trends over years to be significant for climate mitigation purposes (Don et al., 2023). Additionally, it will be challenging to identify sites where it would be beneficial to sample more frequently without sampling all sites frequently to assess spatial and temporal variability at all sites.

4.3. Temporal variability and monitoring implications

The variability observed in short-term changes in SOC, particularly in the FS dataset, may reflect not only spatial heterogeneity, but also short-term changes in soil carbon inputs, decomposition rates or management practices (Wuest, 2014; Gocke et al., 2023). This reinforces the idea that small, short-term changes in SOC may represent noise rather than true trends. Nerger et al. (2020) studied the SOC stock of agricultural soils in northern Germany at annual intervals over approximately 10 years. They concluded that annual sampling is necessary to accurately capture short-term variations in soil properties in order to identify long-term trends (Nerger et al., 2020). Similarly, Desaules (2012) argued that annual measurements are likely to produce highly variable results, but that the denser and longer time-series of data would allow for characterization of the noise within the dataset arising from multiple sources of error. Quantification of the noise from frequent sampling would over a longer time period allow for the long-term trend to be distinguishable from the short-term variability (Desaules, 2012), however it is still uncertain whether such errors are consistent over time. Our temporally close FS observations often show high variability, which may be due to random errors, spatial variability as well as a slight shift in sampling location due to destructive sampling. As the expected persistent year-to-year changes in SOC content are small compared to the measurement variability (uncertainty), a few annual measurements of SOC content in SMNs are unlikely to provide reliable short-term trends. This is also recognized in most protocols for crediting soil carbon sequestration where sampling frequencies of 4–5 years are recommended as such initiatives must be based on relatively long-term monitoring of changes in existing soil carbon stocks (British Society of Soil Science, 2023; Dupla et al., 2024). Statistical analyses of SOC content or stock changes could be strengthened if replicates were available from the sampled sites, regardless of sampling frequency. Currently in the NSG, each site-depth has only a pooled sample, and spatial variability cannot be quantified nor can the SOC content from different years or sites be compared directly using statistical methods.

In summary, our results support the argument that decadal sampling may provide a sufficient balance between feasibility and trend detection, particularly in large-scale SMNs with limited resources. While some studies advocate more frequent sampling intervals (Desaules, 2012; Nerger et al., 2020) the variability observed in annual measurements suggests that such frequency is not always necessary nor informative, indicating that decadal sampling might be a more prudent choice for SMNs, which has been suggested previously (e.g., by Saby et al., 2008; Goidts et al., 2009). Furthermore, as shown in our simulation, intervals of 3–5 years may provide a useful compromise, reducing the likelihood of over-reliance on short-term, potentially anomalous data points, while still maintaining sufficient resolution for trend detection and estimation of uncertainty associated with spatial variability and annual variations. Lastly, it is important to note that this study only assesses the variability in SOC content; changes in SOC stock may also derive from changes in bulk density (Poeplau et al., 2017), e.g., caused by compaction (da Silva et al., 1997), as well as from erosion or deposition of soil, which changes the soil layers that are compared in time. Thus, changes in SOC stock over shorter and longer sampling intervals may show different patterns than the SOC content. However, in relation to carbon credits and C sequestration, the SOC content dynamic is extremely important, as an increase in SOC content always represents a carbon sink function.

4.4. Future directions and challenges

To meet the long-term goal of SOC monitoring for carbon sequestration and climate change mitigation, the design of future SMNs should carefully consider the trade-off between sampling frequency and resource limitations. Our study suggests that decadal or slightly more frequent (3–5 years) sampling could adequately capture SOC trends without the need for costly annual monitoring. However, future studies should explore the integration of decadal sampling with more frequent sampling to balance broad-scale monitoring with finer temporal detail.

From an operational perspective, a decadal monitoring scheme may suffer from discontinuities in the details of practical field sampling procedures, sample handling and SOC analysis (Robinson et al., 2024). This may introduce additional uncertainties on top of those caused by, e.g., incomplete information on management practices and environmental factors. For an SMN the size of Denmark's (approximately 500 sites), it could be suggested to implement a 3–5 year interval monitoring scheme, with annual sampling of 100–150 sites in a fixed rotation, similar to the rolling sampling cycle implemented in the UK Countryside Survey (Robinson et al., 2024). Such a system can help to maintain continuity of expertise in field work and laboratory capacity, thus ensuring consistent data quality over time (Robinson et al., 2024). Alternatively, a subset of sites, randomly selected to proportionally represent soil types and land uses, could be sampled more frequently (every 3–5 years), while maintaining the decadal sampling for the remaining sites, thereby only increasing the resource expenses slightly while gaining substantial temporal resolution in the SMN. However, the data from the subset should not necessarily be considered to be equally spatially representative as the larger SMN but rather an indicator of the direction and magnitude of change of various soil parameters in the short-term.

To optimize resources, more frequent sampling could focus on the top 0–50 cm of soil, where SOC changes occur more rapidly. This approach would reduce labor and costs compared to deeper sampling, especially as obtaining empirical measurements of soil bulk density at greater depth can be challenging. It is still important to include the 25–50 cm subsoil layer in SMNs as agricultural management can have significant impact below the plough layer (Skadell et al., 2023; Meurer et al., 2024). In the Danish SMN, subsoil increases in SOC stock were observed to compensate for, and even outweigh, topsoil SOC stock losses between 2008/09 and 2018/19 (Harbo et al., 2023a). While the mechanism behind this remain speculative, it may include increased prevalence of deep-rooted crops (Harbo et al., 2023a). Carbon storage and transformation in deeper subsoil (e.g., 50–100 cm) is spatially heterogeneous (Chabbi et al., 2009; Heitkötter and Marschner, 2018) and changes occur more slowly making it difficult to assess statistically. Therefore, inventories at these depths may not need to be conducted more frequently than once per decade.

Other options to be explored, beyond the scope of this paper, relate to advances in remote sensing and other non-invasive techniques for SOC content estimation (Croft et al., 2012; Angelopoulou et al., 2019; Abdulraheem et al., 2023; Li et al., 2024), which could complement traditional soil sampling methods by providing more continuous data without the need for labor-intensive sampling campaigns. The integration of these technologies with traditional sampling approaches could help to reduce costs while increasing the temporal resolution of SOC content and SOC stock monitoring.

5. Conclusion

This study shows that decadal sampling is generally comparable to more frequent sampling and is sufficient to monitor long-term SOC content trends in agricultural soils in Denmark. Although annual sampling can detect short-term fluctuations, the associated increase in labor and cost may not justify the improvement in trend detection, especially for large-scale soil monitoring networks; additionally, short-term changes in SOC content may not be relevant to the overall trend in SOC content change. Our simulations suggest that an interval of 3–5 years, potentially in combination with a rolling sampling campaign, may provide a compromise, allowing for better detection of SOC dynamics at the national scale without the need for annual sampling. A strategic approach that balances decadal sampling with rotational intensified sampling could optimize resource use while maintaining the ability to monitor meaningful SOC changes at meaningful time scales, ensuring continuity in annual sampling and SOC analyses, and maintaining the expertise necessary to ensure consistent, high-quality data over time. Intervals of 3–5 years can also allow researchers, stakeholders and policy makers to compare predicted changes in SOC content to observations, thereby supporting national greenhouse gas emission reporting.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2025.e00931.

Data availability statement

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

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