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Changes in organic matter contents and carbon stocks in Dutch soils, 1998–2018

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ABSTRACT

Changes in soil organic matter (SOM) content and soil organic carbon (SOC) stock in the 0–30 cm and 30–100 cm soil layers between 1998 and 2018 in the Netherlands were estimated by repeated sampling of 1152 locations in the Soil Sampling Programme (SSP). These locations were selected following a stratified simple random sampling design. We discuss various barriers we met: restricted accuracy of information on soil bulk density, uncertainties due to positional errors, differences in sampling support, and changes in laboratory analysis methods since 1998. Domains of interest such as mineral soils were defined either on the basis of the stratification of the SSP sample (geomatching) or on the basis of soil profiles observed at the selected locations (classmatching). The mean SOM content changed significantly in the 30–100 cm layer (-17.68 $\mathrm{g\,kg^{-1}}$) in the entire area of interest (non-built-up area in the Netherlands) between 1998 and 2018 (at a 5% significance level). A decrease in SOM content between 1998 and 2018 could be shown for the 0–30 cm layer in mineral soils under cropland if classmatching was applied (at a 5% significance level), but no change could be shown in this layer in the remaining domains of interest, whether geomatching or classmatching were applied. For the 30–100 cm layer in mineral soils, significant changes in mean SOM content were shown by classmatching: −8.59 $\mathrm{g\,kg^{-1}}$ under cropland and −4.75 $\mathrm{g\,kg^{-1}}$ under grassland. The calculations indicate that SOC stocks decreased between 1998 and 2018 in both the 0–30 cm and the 30–100 cm layer of mineral soils under both cropland and grassland. The accuracy of the bulk density data needs to be improved in future measurements to increase the accuracy of calculations of the SOC stock changes.

1. Introduction

Soil organic carbon (SOC) is an important topic in climate policy (Banwart et al., 2014), which aims to reduce losses in the SOC stock and explore the potentials for SOC sequestration. The United Nations Framework Convention on Climate Change (UNFCCC) (United Nations, 1992) and its operationalizations in the Kyoto Protocol (United Nations, 1998) and the Paris Agreement (United Nations, 2015) require signatory countries to monitor and report changes in the SOC stock. This has resulted in regulations, protocols and guidelines for monitoring and reporting, such as Regulation (EU) 525/2013 (European Union, 2013a), Decision 529/2013 and Regulation 2018/841 on greenhouse gas emissions and removals resulting from activities relating to land use, land-use change and forestry (LULUCF) (European Union, 2013b; European Union, 2018), a soil sampling protocol to certify the changes in organic carbon stock in mineral soils of the European Union (Stolbovoy et al., 2007), and guidelines for measuring and modelling SOC stocks and stock changes in livestock production systems (FAO, 2018).

To support their policies on SOC stocks and fulfil international requirements on reporting changes in SOC stocks, countries have developed strategies to monitor SOC stocks and changes therein nationwide. Although developed in line with international guidelines and regulations, these monitoring strategies can differ with respect to:

1. target quantities (e.g. SOC content or SOC stock, and changes or trends therein, in layers at various depths);
2. domains of interest (e.g. nationwide or focused on specific forms of land use);
3. sampling strategy (random, targeted or convenience);
4. sampling density (e.g. grid distance in case of orthogonal grid samples);
5. inference method (design-based or model-based);
6. sample support (number, configuration and dimensions of the aliquots taken at the sampling locations);

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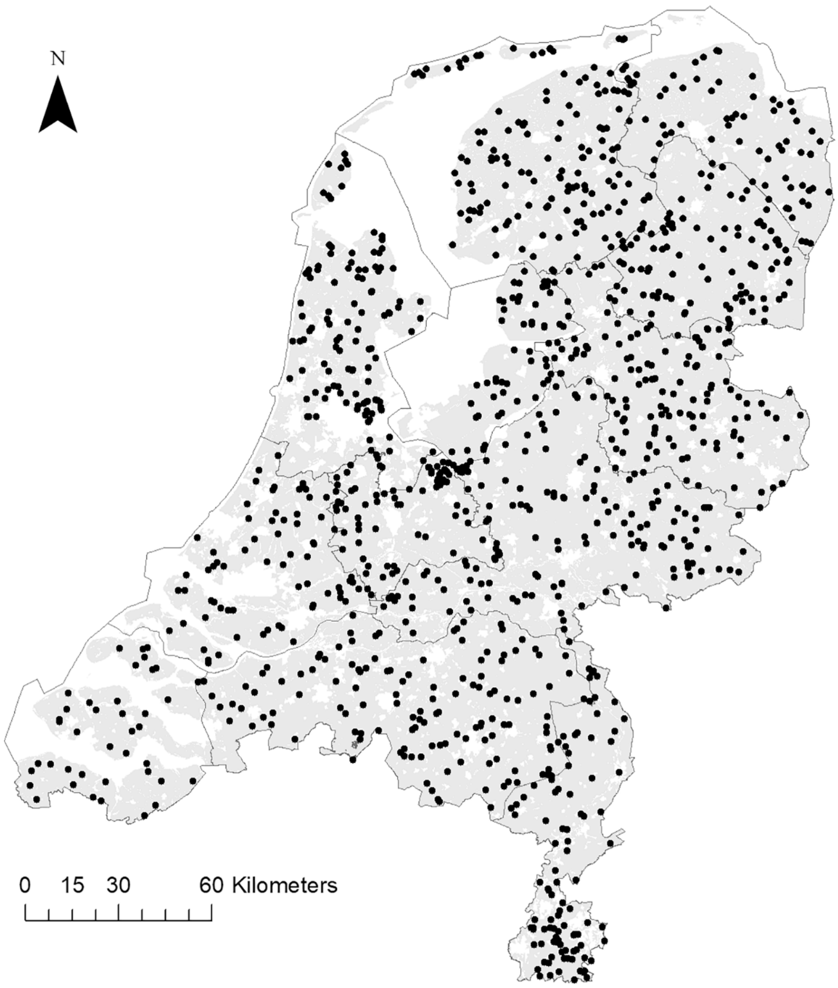

Fig. 1. Locations of the SSP (Soil Sampling Programme of the Netherlands) revisited in 2018.

7. method for laboratory analysis of SOC content;
8. method for determining soil bulk density (e.g. measurements using sample rings or estimates using pedotransfer functions).

See Schrumpf et al. (2011) and Gubler et al. (2019) for summaries of studies in European countries on changes in SOC stocks by repeated inventories at a regional scale. An important factor in making choices about the system for SOC stock monitoring is the way in which soil reference data were collected in the past, in particular if changes in SOC stock have to be determined since the collection of the reference dataset. In the Netherlands, a nationwide soil reference dataset from the Soil Sampling Programme (SSP) (Visschers et al., 2007) is available. The dataset includes data on soil organic matter (SOM) content and texture for soil horizons. These data were collected between 1994 and 2001 at 1396 locations that were selected following a stratified simple random sampling design. In 2018 and 2019, the SSP locations were revisited and data on actual SOM and SOC content as well as on texture and soil bulk density were collected and compared with the data from the period 1994–2001. In the following, we refer to the actual situation with '2018' and to the reference period with '1998'.

The aim of this paper is to present mean SOM contents and SOC stocks and changes between 1998 and 2018 in the non-built-up area with terrestrial soils in the Netherlands, and in sub-areas (domains of interest) such as cropland and grassland on mineral soils. We consider the soil carbon pool, and not other pools (biomass, roots, litter), as we focus on the long-term carbon cycle. We aim to quantify changes in SOM contents and SOC stocks, rather than explaining them. Therefore, we focus on reporting changes, which can serve as a starting point for further research on explanations. We discuss the several barriers we met in the estimation of changes in SOC stocks, and how they may affect the accuracy of estimated changes: restricted availability of accurate information on soil bulk density, several uncertainties due to positional errors, differences in sampling support, and changes in laboratory analysis methods since 1998. Furthermore, we discuss how the method followed in this study relates to methods of measuring SOC changes in other countries and regions, and we compare the observed changes in SOM content and SOC stock with results of previous studies in the Netherlands and other countries.

2. Materials and methods

2.1. Sampling design of the Soil Sampling Programme

To estimate changes in SOM content and SOC stock, we used the sampling design of the Soil Sampling Programme (SSP) for the Netherlands, which was developed more than 30 years ago when the soil map of the Netherlands (at a scale of 1:50,000) was about to be finished. The SSP aimed for a quantitative and actual description of the soil properties within the map units of this soil map (Visschers et al., 2007). A random sampling approach was taken in the SSP, to avoid subjectivity and enable valid statistical inference. After two try-out projects in the years 1988–1990, field data were collected nationwide in the years 1994–2001 at a total of 1396 locations, following a stratified simple random sampling design. The primary stratification was based on nine water table classes. These water table classes describe the seasonal fluctuations in water table depths. In the Netherlands, the water table is generally present between 0 and 200 cm below the ground surface and thus influences physical, chemical and biological soil processes, which makes water table depth an important factor in crop production and ecology. Water table classes are therefore mapped concurrently with soil surveys and depicted on soil maps. The primary strata were further divided into secondary strata to obtain pedologically homogeneous strata and accurate information for specific domains of interest, such as significant nature areas. This resulted in 94 strata.

The target area covered by the SSP concerns all non-built-up areas with terrestrial soils in the Netherlands; that is, all land classified as such in the 1:50,000 National Soil Map (2,870,671 hectares, about 69% of the total area of the Netherlands). Of the 1396 SSP locations, 244 (17%) locations could not be revisited during the fieldwork campaign in 2018. Of these, 138 locations (10%) were not accessible because of urbanization, infrastructural works or structures such as fences; 45 locations (3%) could not be revisited because the landowners refused access; and the landowners of 61 locations (4%) could not be asked for the necessary permission to access their land because they could not be traced. Given the various reasons, it seems unlikely that the non-response in 2018 caused a bias in the estimation of changes in SOM content and SOC stock. Fig. 1 shows the 1152 sample locations that were revisited in 2018.

2.2. Collection of aliquots

We adopted the configuration of the LUCAS inventory (Fernández-Ugalde et al., 2017) to collect aliquots at the SSP sample locations. At each of these locations, five soil cores were taken: the first at the central SSP point and the next four at distance of two metres from this central point in the cardinal directions north, east, south and west. The soil cores were taken with a single gouge auger, with a 100 cm length and 3 cm diameter, from the 0–30 cm and 30–100 cm layers. For each depth, the five soil cores were mixed to form a composite aliquot and stored in a bag.

2.3. Laboratory analyses

The soil samples were dried at 40 °C, milled and sieved to 2 mm, and stored in a glass jar (NEN, 2012b). SOM was determined by loss on ignition (550 °C) (NEN, 2014), SOC as elemental C following dry combustion (550 °C) (Yeomans and Bremner, 1991; Soon and Abboud, 1991; ISO, 1995), total carbon (TC) – which includes SOC and inorganic carbon (TIC) – by dry combustion at 1150 °C (NEN, 2012a), and total inorganic carbon (TIC) up to 1000 °C (ISO, 1995). Clay content was determined through density fractionation (NEN, 2014), and M50 (median of sand fraction 50–2000 μm) by NIRS (Reijneveld et al., 2022). Reference samples were always included to check the analytical precision.

Until recently, only SOM content was reported in agricultural practice in the Netherlands. The SOM content for soils rich in organic matter (all soils under grassland and peaty arable soils) was determined by loss on ignition using corrections for inorganic carbonates (TIC) and percentage clay in the soil. For all other soils, SOC ×2 was reported. There is, however, considerable uncertainty about this conversion factor (e.g. Rosell et al. (2001),Sleutel et al. (2007), Pribyl (2010)), which may have affected the reported SOM contents. Therefore, both SOM and SOC are now reported in agricultural practice.

2.4. Estimation of soil bulk density

Accurately determined soil bulk densities are indispensable for estimating SOC stocks. Accurate estimates can be obtained from aliquots that are collected with cylindric sample rings, for instance with a volume of 100 cm^3. Taking these aliquots is labour intensive and thus expensive, however. As a less expensive, but probably less accurate, alternative to sample rings, we used a single gouge auger to collect aliquots with a known volume. However, the soil bulk densities determined with the single gouge auger appeared to be unreliable due to the dry conditions during fieldwork and were not used in the analyses. As an alternative to a direct determination of soil bulk density from aliquots, we estimated soil bulk densities using linear relationships with SOM content, median particle size of the sand fraction (M50), loam content and clay content as explanatory variables. These linear relationships are also referred to as pedotransfer functions (PTFs, see van Looy et al. (2017) for a review). We estimated soil bulk densities using PTFs given by Wösten (1997). For sandy soils (clay content < 80 g kg^{-1}), this PTF is

$$y = \left(-1.984 + 0.01841 \cdot x_1 + 0.032 \cdot x_2 + 0.00003576 \cdot x_4^2 + 67.5 \cdot x_3^{-1} + 0.44 \cdot \ln(x_3)\right)^{-1} \tag{1}$$

where y is the soil bulk density [g cm^{-3}], x_1 the SOM content [10^{-1} g kg^{-1}], x_2 an indicator with value 1 for the topsoil layers (0–30 cm) and 0 for subsoil layers (30–100 cm), x_3 the M50, and x_4 the loam content [10^{-1} g kg^{-1}]. For clayey soils (clay content $\geqslant 80$ g kg^{-1}), the PTF is

$$y = \left(0.603 + 0.003975 \cdot x_5 + 0.00207 \cdot x_1^2 + 0.01781 \cdot \ln(x_1)\right)^{-1} \tag{2}$$

where x_5 is the clay content [10^{-1} g kg^{-1}]. For peaty soils (SOM content $\geqslant 150$ g kg^{-1}), the PTF for topsoil layers (0–30 cm) is

$$y = 1.457 - 0.578 \cdot \log(x_1) \tag{3}$$

and for subsoil layers (30–100 cm) the PTF is

$$y = 1.251 - 0.564 \cdot \log(x_1) \tag{4}$$

2.5. Land use

To enable estimations to be made for domains with a specific land use, categorizations were based on LGN2018 (Hazeu et al. (2020)), the national grid-based five-metre-resolution land-use map of the Netherlands. We first zoomed in on the non-built-up area of the Netherlands. Of this area, we selected the agricultural area, which we divided into cropland and grassland. An overlay with the sampling locations was created to divide the sampling units into the different land uses. The same land-use map was used for both the 1998 and 2018 data.

2.6. Statistical inference

Mean SOM contents and SOC stocks for the target area as a whole can be estimated using the equations for stratified simple random sampling given by de Gruijter et al. (2006) and Visschers et al. (2007) and the relative areas of the strata. Estimates can also be made for specific subareas (domains of interest), such as mineral and organic soils, grassland and cropland. The domains of interest considered in this study are summarized as follows:

1. the area mapped in the 1:50,000 national soil map, i.e. all non-built-up areas;

Table 1
Mean SOM contents [$g\,kg^{-1}$] for the total area of interest of the Soil Sampling Programme (2,870,671 hectares). Standard errors in parentheses. Significant differences in bold (at a 5% significance level).

Layer	1998	2018	2018–1998
0–30 cm	64.97 (1.79)	63.92 (1.38)	−1.06 (1.56)
30–100 cm	68.43 (2.60)	50.75 (1.61)	**−17.68** (2.30)

2. within 1: mineral soils and organic soils as classified in the 1:50,000 national soil map, i.e. geomatching;
3. within 1: mineral soils and organic soils as classified on the basis of the soil profiles observed at the sampling locations, i.e. classmatching;
4. within 2: cropland and grassland in 2018;
5. within 3: cropland and grassland in 2018.

Estimates for sub-areas or domains of interest can be obtained in two different ways, depending on how the domains of interest are defined. The first way is to define domains of interest on the basis of the stratification in the SSP sample. Estimates can be made for each stratum separately using the equations for simple random sampling, and for groups of strata using the equations for stratified simple random sampling and the relative areas of the strata (de Gruijter et al., 2006). The second way is to define domains of interest that do not coincide with strata, for instance domains derived from a map that was not used in the stratification, such as a land-use map, or from observations at the sampling locations. In these cases, the equations for domain estimates given by Visschers et al. (2007) can be used.

The distinction between the two methods of domain estimation is particularly relevant if estimates for specific soil types are required, because the soil types can be derived either from the map that was used in the stratification or from the soil profile descriptions made at the sampling locations. If the soil map is used to define a domain, an estimate is made for a specific soil type for a known area to which that soil type was assigned in the soil map used in the stratification. It should be noted that this area can cover soil types other than the soil type of interest alone, since the soil map is a generalization of reality, with percentages of correctly classified soil types that are generally below 100%. If the domain of interest is defined on the basis of the soil profile descriptions, we can be sure that the estimate concerns the soil type of interest only. The area of this soil type is of course unknown, since perfect soil maps do not exist. However, this area can be estimated. The distinction between domain estimates for soil types on the basis of the soil map or the soil profile descriptions is similar to the distinction between geomatching and classmatching made by Lettens et al. (2004). Appendices A and B summarize the estimation procedure based on the soil map (geomatching) and the soil profile descriptions (classmatching), respectively.

In this study, mineral soils and organic soils were separated using geomatching and classmatching. In geomatching, the stratification of the SSP, based on the soil map of the Netherlands, was used. Strata covering map units of mineral soils with organic layers starting deeper than 40 cm were not included, to restrict the domain as much as possible to soils consisting of mineral material alone up to 100 cm depth. In classmatching, the distinction between mineral and organic soils was made on the basis of the Dutch system of soil classification (de Bakker and Schelling, 1989) and the soil profiles observed at the sampling locations of the SSP. A soil is classified as organic if an organic layer starts within 40 cm depth. Otherwise, the soil is classified as mineral. This implies that, in mineral soils, organic layers can be present at depths greater than 40 cm.

Since the sample locations of the SSP were revisited, significance testing using paired t-tests was applied to make inferences about changes in SOM contents between 1998 and 2018. On the basis of the Central Limit Theorem we assumed that the sample means of changes are normally distributed, given the sample size. Inference in terms of statistical significance could not be made about the estimated changes in SOC stock, because the uncertainties related to soil bulk density could not be quantified completely. Only observations on SOM content were available for 1998, whereas both SOM content and SOC content were measured in 2018. To avoid possible bias in estimated changes, SOC contents were derived for both 1998 and 2018 by multiplying SOM contents by 0.5.

Because the data on SOM content collected during the SSP in 1998 concern soil horizons, the contents in 1998 for the 0–30 cm and 30–100 cm layers had to be estimated by weighting. It should be noted that SOM content concerns mass rather than volume. Therefore, soil bulk densities (Section 2.4) are needed to calculate the weights. Suppose that, in a layer of fixed depth, n soil horizons are present with thicknesses $t_i, i = 1 \cdots n$, which sum to the thickness of that layer. The weighting is now as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i t_i d_i}{\sum_{i=1}^{n} t_i d_i} \tag{5}$$

where x_i is the SOM content in the ith horizon (mass fraction, i.e. $g\,kg^{-1}$), t_i the thickness of the ith horizon within the layer [cm], and d_i the soil bulk density of the ith horizon [$g\ cm^{-3}$].

Differences in methods to determine SOM content and SOC stock between 1998 and 2018 can cause bias in estimated changes in SOM content and SOC stock. Appendix C provides an overview of methodological differences between 1998 and 2018, the expected effects on estimated changes in SOM content and SOC stock, and the measures to reduce possible bias.

3. Results

3.1. Changes in SOM content

The estimated mean SOM contents and changes therein between 1998 and 2018 for all soils sampled in the SSP are given in Table 1.

The first part of Table 2 summarizes mean SOM contents and changes in mean SOM contents for all strata of the SSP with mineral soils only, according to the Soil Map of the Netherlands (1:50,000), see Fig. 2. This is similar to geomatching introduced by Lettens et al. (2004). There is no significant indication of a change in mean SOM content in the 0–30 cm layer between 1998 and 2018 for the area of 1,039,521 ha classified as mineral soils (at a 5% significance level). For the 30–100 cm layer, a significant change in SOM content is shown (increase of 0.29 $g\,kg^{-1}$). Note that the area is exactly known from the soil map, but that this area does not necessarily include mineral soils alone, since the accuracy of the map is restricted to a certain correctly classified percentage.

Table 2 also presents mean SOM contents and changes for the real but unknown area of mineral soils, obtained by domain estimation on the basis of the soil classifications of the soil profiles that were observed at the sampling locations during the SSP field campaign in 1998. This is similar to classmatching as described by Lettens et al. (2004). Note that soils classified as mineral soils according to the Dutch system of soil classification (de Bakker and Schelling, 1989) may have organic layers at depths greater than 40 cm. This might explain the relatively high mean contents and stocks in the 30–100 cm layer. The area with mineral soils is estimated to be 2,474,454 ha. Compared to the results of geomatching in Table 2, classmatching results in higher SOM contents, in particular in the 30–100 cm soil layer. Furthermore, a significant decrease in mean SOM content between 1998 and 2018 can be seen in this layer at the 5% significance level, whereas geomatching indicated a significant increase. These opposing results can be explained by the difference in area of interest: geomatching informs about changes in the area of mineral soils as indicated by the soil map, whereas classmatching

Table 2
Mean SOM contents [$g\,kg^{-1}$] for mineral and organic soils using geomatching and classmatching. Standard errors in parentheses, significant differences in bold (at a 5% significance level).

Soil type	Method	Layer	1998	2018	2018–1998
Mineral	Geomatching	0–30 cm	39.86 (1.10)	41.19 (1.24)	1.33 (1.27)
Mineral	Geomatching	30–100 cm	18.28 (0.80)	17.83 (0.77)	−0.45 (0.87)
Mineral	Classmatching	0–30 cm	49.72 (1.29)	47.84 (1.41)	−1.89 (0.98)
Mineral	Classmatching	30–100 cm	34.20 (1.67)	28.02 (1.47)	−**6.18** (1.36)
Organic	Geomatching	0–30 cm	159.18 (12.07)	163.15 (8.15)	3.97 (10.17)
Organic	Geomatching	30–100 cm	280.77 (16.34)	208.20 (10.47)	−**71.57** (14.80)
Organic	Classmatching	0–30 cm	186.36 (15.05)	181.41 (11.28)	−4.95 (11.44)
Organic	Classmatching	30–100 cm	326.77 (21.82)	231.49 (15.04)	−**95.28** (15.82)

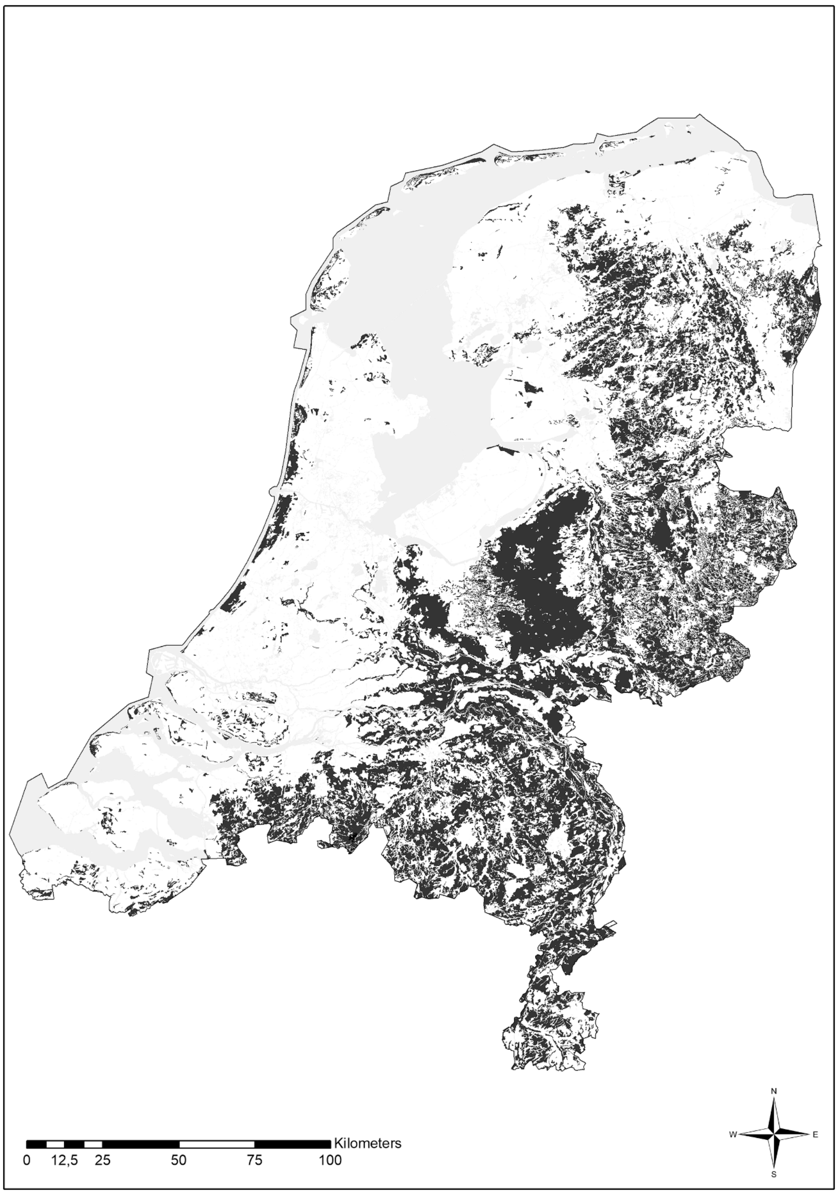

Fig. 2. Area of mineral soils, as indicated by the Soil Map of the Netherlands (1:50,000).

informs about changes in the real but unknown area of mineral soils. Again, it should be noted that, according to the Dutch classification system, mineral soils may have organic layers starting at depths greater than 40 cm.

Table 2 also gives mean SOM contents and changes in mean SOM contents for all strata of the SSP with soils with an organic layer within 30 cm depth, according to the Soil Map of the Netherlands (1:50,000), i. e. geomatching. Fig. 3 shows the area (393,685 hectares) of these map units. A significant decrease in mean SOM content between 1998 and 2018 is shown for the 30–100 cm layer (at a 5% significance level). Table 2 furthermore presents mean SOM contents and changes for the real but unknown area of soils with an organic layer within 100 cm

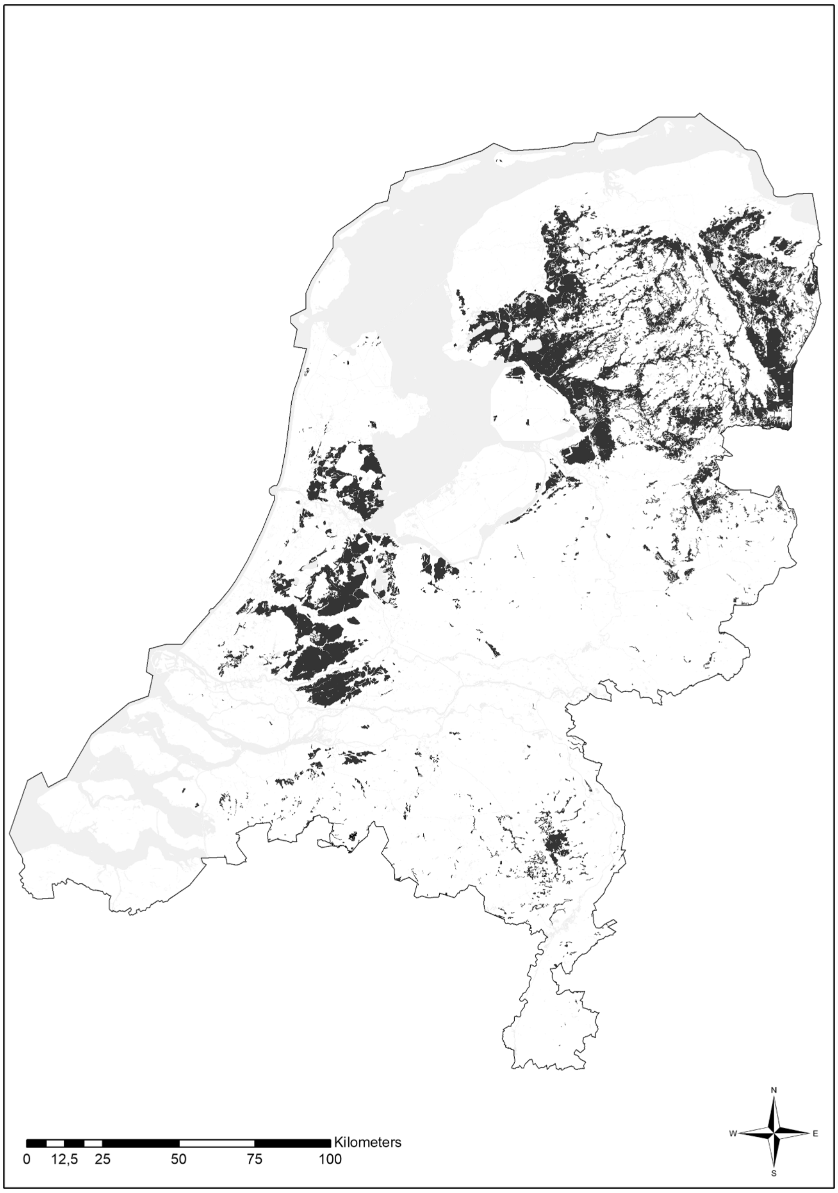

Fig. 3. Area of soils with peaty layers within 30 cm depth, as indicated by the Soil Map of the Netherlands (1:50,000).

Table 3
SOM contents [$g\,kg^{-1}$] and SOC stocks [ton/ha] in the 0–30 cm and 30–100 cm layers for the domain of cropland on mineral soils. Domains are defined on the basis of soil profile descriptions made at the sampling points during the SSP (1998), i.e. classmatching. Standard errors in parentheses. Significant changes in bold (at a 5% significance level).

Layer	Year	SOM content [$g\,kg^{-1}$]	SOC stock [ton/ha]
0–30 cm	1998	38.34 (2.44)	78.56
30–100 cm	1998	28.23 (2.76)	123.77
0–30 cm	2018	34.55 (2.42)	69.53
30–100 cm	2018	19.64 (1.72)	93.53
0–100 cm	1998	32.54 (3.72)	199.51
0–100 cm	2018	27.10 (4.21)	163.09
0–30 cm	2018–1998	−**3.80** (1.31)	−9.13
30–100 cm	2018–1998	−**8.59** (2.33)	−30.19
0–100 cm	2018–1998	−**5.62** (1.41)	−37.64

depth, obtained by domain estimation on the basis of the soil profile descriptions made during the SSP field campaign in 1998, i.e. classmatching. The area is estimated at 364,038 ha. Compared to the results of geomatching in Table 2, classmatching results in higher SOM contents. This can possibly be explained by the accuracy of the Soil Map of the Netherlands (1:50.000) used in the stratification: a part of the area mapped as organic soils might be incorrectly classified. The results in Table 2 show significant decreases in mean SOM content in the soil at 30–100 cm depth (at a 5% significance level).

Table 3 presents the domain estimates of SOM contents and SOC

Table 4
SOM contents [g kg^{-1}] and SOC stocks [ton/ha] in the 0–30 cm and 30–100 cm layers for the domain of grassland on mineral soils. Domains are defined on the basis of soil profile descriptions made at the sampling points during the SSP (1998), i.e. classmatching. Standard errors in parentheses. Significant changes in bold (at a 5% significance level).

Layer	Year	SOM content [g kg^{-1}]	SOC stock [ton/ha]
0–30 cm	1998	56.47 (2.24)	103.66
30–100 cm	1998	37.73 (2.43)	144.71
0–30 cm	2018	55.71 (2.33)	100.835
30–100 cm	2018	32.98 (2.27)	127.15
0–100 cm	1998	49.19 (6.51)	248.91
0–100 cm	2018	42.46 (3.75)	228.56
0–30 cm	2018–1998	−0.75 (1.37)	−2.81
30–100 cm	2018–1998	**−4.75** (1.72)	−17.56
0–100 cm	2018–1998	−6.72 (4.64)	−20.22

stocks in the 0–30 cm and 30–100 cm layers for the domain of cropland on mineral soils in 1998 and 2018. The domains are defined based on the soil profile descriptions and LGN2018. Note that mineral soils may have organic layers at depths greater than 40 cm. This might explain the relatively high mean contents and stocks in the 30–100 cm layer, besides impurities in the soil map. Furthermore, it should be noted that uncertainties in soil bulk density are not accounted for in SOC stock estimations. Only locations for which data are available in both 1998 and 2018 are considered in the estimation of changes (i.e. paired observations). The area of croplands on mineral soils is estimated at 964,720 ha.

Table 4 presents the domain estimates of SOM contents and SOC stocks in the 0–30 cm and 30–100 cm layers for the domain of grassland on mineral soils in 1998 and 2018. The domains are defined based on the soil profile descriptions and LGN2018. Again, note that mineral soils may have organic layers at depths greater than 40 cm, which might explain the relatively high mean contents and stocks in the 30–100 cm layer. Also note that uncertainties in soil bulk density are not accounted for in the SOC stock estimations. Changes are estimated on the basis of paired observations only. The area of grassland on mineral soils is estimated at 896,303 ha.

From the results in Tables 3 and 4, rates of change can be calculated that indicate that SOC stocks in mineral soils under cropland decreased faster than under grassland: for mineral soils under cropland, rates of change were found of −0.57%/yr, −1.22%/yr and −0.91%/yr for the 0–30 cm, 30–100 cm and 0–100 cm layers, respectively, whereas for mineral soils under grassland these rates were −0.14%/yr, −0.61%/yr and −0.41%/yr, respectively. We emphasize that SOC stock estimates depend on assumptions on soil bulk density. We used the texture data from 2018 to estimate the soil bulk densities in 1998 and 2018 with PTFs, to avoid systematic errors due to differences in measurement methods between 1998 and 2018 (see Appendix C).

4. Discussion

4.1. Errors in estimated changes

Before drawing conclusions from the estimated changes in SOM content and SOC stock between 1998 and 2018, as presented in the previous section, it is important to analyse whether differences in field practices and laboratory methods between 1998 and 2018 could result in systematic errors (see Appendix C). The first difference concerns positional accuracy. The locations visited in 1998 could not be marked in the field, so these locations had to be positioned again in 2018 based on the randomly selected spatial coordinates. In 2018, the selected spatial coordinates were positioned using GPS, whereas in 1998 a much less accurate positioning procedure was followed based on a 1:25,000 topographical map and a ruler guide. However, the assumption that positional errors are random rather than systematic seems reasonable.

The second difference concerns changes in sample support. In 1998, aliquots were taken from soil horizons with an Edelman auger, whereas in 2018 soil cores were collected with a single gouge auger from the 0–30 cm and 30–100 cm layers. For 1998, the SOM contents and SOC stocks in the 0–30 cm and 30–100 cm layers were calculated from the data for soil horizons by weighting. We assume that these differences in sample support result in random rather than systematic errors in estimated changes in SOM content and SOC stock.

An important question in estimating changes in SOC stock is how to deal with changes in soil bulk density. The soil bulk density is calculated using PTFs for Dutch soils (Wösten et al., 2001; Wösten, 1997). The same PTFs were used to calculate the density in 1998 and 2018; therefore, these functions are assumed to remain valid in a changing environment. The functions were derived with data up to 1997, so new data collected afterwards are not represented in the PTFs. The assumption that the relation between the bulk density and several soil parameters remains equal could be valid, but the feature space might differ between 1998 and 2018, possibly causing a difference in soil bulk density calculations and subsequently SOC stock calculations. PTFs have explanatory variables on texture. The texture data collected in 1998 were based on field estimates by soil surveyors, whereas the data collected in 2018 were based on laboratory measurements. To avoid systematic errors due to differences in measurement methods between 1998 and 2018, we estimated SOC stock changes between 1998 and 2018 on the basis of texture data from 2018 only (see Appendix C). To account for possible changes in soil bulk density in SOC stock monitoring, more accurate data on soil bulk density are needed. Besides this, soil bulk densities in topsoils may show seasonal variations, particularly in croplands, which should be considered when monitoring changes in SOM content and SOC stocks. Furthermore, the monitoring of SOC stock changes in mass layers rather than depth layers is worth considering, by applying an equivalent soil mass procedure as proposed by Wendt and Hauser (2013), since this avoids errors due to changing soil bulk densities and does not require soil bulk density measurements or PTF estimates.

4.2. Geomatching or classmatching?

Domain estimates for mineral soils and organic soils were made by geomatching and classmatching. The differences in results (see Table 2) show that the choice between domain estimation by geomatching or classmatching is relevant. The estimates made by geomatching concern the areas of a specific soil class as delineated in the soil map, including the impure parts of these areas. The estimates made by classmatching for a certain soil class are closer to the physical reality, because they concern the soil class as observed at the sampling locations, without the effect of impurities. The area of the soil class is not known, since the perfect soil map does not exist, but is estimated from the sample. If the purpose of monitoring is to describe changes in mean contents and stocks in a specific soil class such as mineral soils as accurately as possible, and the exact spatial distribution of this soil class is less important, then classmatching should be chosen. If map units of the soil map are considered as administrative units for which changes in mean contents and stocks need to be monitored, then geomatching should be applied.

4.3. Possible explanation for estimated SOC reductions in organic soils

This study was set up to quantify changes in SOM contents and SOC stocks between 1998 and 2018 in soil layers rather than to explain these changes. However, we do suggest a possible explanation for the relatively large SOC reductions in soils with an organic layer (Table 2). These reductions can possibly be explained by the oxidation of organic material as a result of intensified drainage and deep ploughing of these soils (Hoogland et al., 2012). Table 2 indicates the largest reductions for the 30–100 cm layer. In the Netherlands, the top of organic layers is found at shallow depths, say between 0 and 100 cm, and the thickness can be more than 100 cm. Loss of organic material results in subsidence, which means that the depth to the mineral subsoil reduces. This effect is most visible in the results for the 30–100 cm layer. Note that, if the depth to the mineral subsoil was still larger than 30 cm or 100 cm in 2018, the loss of organic material between 1998 and 2018 would be underestimated for the 0–30 cm and 30–100 cm layers, because only SOM contents and SOC stocks in depth layers are considered in this study and soil subsidence is not accounted for.

4.4. *Comparison with studies in other countries*

In a review of methods for measuring SOC changes in soils in various countries and regions, Smith et al. (2019) make a distinction between measuring SOC stock changes *directly* by repeated sampling and calculating SOC stock changes *indirectly* by drawing up a full carbon budget to infer SOC stock changes from flux measurements. In this study, we were able to follow the direct approach, since data from the SSP for the Netherlands, collected between 1994 and 2001, were available. Countries such as England and Wales (Bellamy et al., 2005), Denmark (Taghizadeh-Toosi et al., 2014), Belgium (Sleutel et al., 2003), China (Teng et al., 2014), Mexico (Smith et al., 2019), New Zealand (Schipper et al., 2014) and Sweden (Olsson, 2005) also follow a direct approach, the last five of which are participants in the Global Research Alliance of Agricultural Greenhouse Gases (GRA). However, the spatial sampling design, sampling density, sampling depths, sampling frequency and analytical procedures vary between countries, see Schrumpf et al. (2011, Table 1), Smith et al. (2019, Table 2) and Gubler et al. (2019, Table 2) for overviews. For example, the sampling density in the Netherlands is about one sampling location per 25 km^2, which is less dense than in Belgium (18 km^2) and Sweden (10 km^2) but more dense than in Mexico (78 km^2) and New Zealand (202 km^2). In the SSP of the Netherlands, a stratified random sample was designed, whereas in other countries grid sampling (England and Wales (Bellamy et al., 2005), Denmark (Taghizadeh-Toosi et al., 2014)), stratified random grid sampling (Sweden (Poeplau et al., 2015)) or purposive sampling in representative soils (New Zealand (Schipper et al., 2014)) were applied.

An interesting question is how the results obtained in this study for the Netherlands relate to those in other countries with relatively comparable environmental conditions. Lettens et al. (2005) calculated the SOC stock of Belgian croplands and grasslands on mineral soils between 1990 and 2000. Their measurements do not distinguish between an upper and lower layer, but encompass the full 100 cm. Lettens et al. (2005) calculated that the SOC stock in the 0–100 cm layer decreased from 8.8 kg C m^{-2} to 8.4 kg C m^{-2} in cropland, and from 13.9 kg C m^{-2} to 13.0 kg C m^{-2} in grassland. Assuming the decrease in SOC stock to be linear with time, this results in an annual decrease rate of 0.45% and 0.65% for cropland and grassland, respectively. The decrease rates found in this study for the 0–100 cm layer in mineral soils in the Netherlands are 0.91% and 0.41% yearly for cropland and grassland, respectively. This indicates a larger annual decrease in the SOC stock in croplands and a smaller annual decrease in the SOC stock in grassland in the Netherlands between 1998 and 2018 compared to in Belgium between 1990 and 2000.

Sleutel et al. (2003) calculated the SOC stock change in croplands on mineral soils in Flanders, Belgium between 1990 and 1999. The bulk density was estimated using PTFs once and then assumed to be constant in time within the measuring time frame. Using a carbon depth distribution model for top soil (i.e. 0–25 cm), SOC measurements were extrapolated to encompass the full 100 cm. Based on the estimated yearly SOC stock change of −359.7 kton/yr and the area of croplands on mineral soils in Belgium of 359,412 ha (Table 3 in Sleutel et al. (2003)), we estimated the yearly rate of change of the SOC stock in croplands in Flanders between 1990 and 1999 at −1.00 ton/ha. In a study with paired observations at 116 locations in intensively managed arable soils in West Flanders, Sleutel et al. (2006) found an average annual loss of −0.19 ton/ha between 1990 and 2003, which was significant at a 5% significance level but less negative than the trend that was found previously for the whole of Flanders. Using the total SOC stock change in croplands on mineral soils of −37.64 ton/ha between 1998 and 2018 (Table 3), the estimated yearly SOC stock change in the Netherlands amounts to −1.88 ton/ha. This cannot be compared with the magnitudes of the negative annual rates of change found by Sleutel et al. (2003, 2006), given the differences in the monitoring period being considered and in the composition of mineral soils between the two countries. We only note that the direction of the trend is similar: that is, a reduction in SOC stock.

Taghizadeh-Toosi et al. (2014) calculated the SOC stock change in Danish croplands on mineral soils. The bulk density was calculated for every grid cell and every layer (i.e. 0–25, 25–50 and 50–100 cm), based on comparable soil profiles from the Danish national soil dataset. The bulk density was assumed to be constant throughout the measurement period of 1986 to 2009. Integrating over the entire profile and all croplands on mineral soils, the results in Taghizadeh-Toosi et al. (2014) did not indicate a significant change. Only a small and non-significant annual change of −0.20 t C/ha was found, whereas in the Netherlands the previously mentioned annual SOC stock change of −1.88 ton/ha was found.

4.5. *Comparison with previous studies in the Netherlands*

Hanegraaf et al. (2009) analysed trends in SOM contents observed in the period 1984–2004 in sandy soils in four provinces of the Netherlands. In soils under grassland, the 0–5 cm layer was analysed, whereas in maize fields the 0–25 cm layer was analysed. They concluded that their analysis did not support “the prevailing opinion in Europe that SOM content in agricultural land is declining”. Our results in Tables 3 and 4 show significant changes in SOM contents in mineral soils between 1998 and 2018 in the 0–30 cm layer under cropland, but not under grassland.

Reijneveld et al. (2009) concluded that “mean SOC contents in the top part of mineral soils of agricultural land in most regions in the Netherlands tended to increase slightly during the period 1984–2004”, which contrasts with “reports from, e.g. United Kingdom and Belgium that suggest decreasing SOC stocks in arable land possibly due to changes in land use and climate” but agrees with the aforementioned conclusion of Hanegraaf et al. (2009). It should be noted that the findings in Reijneveld et al. (2009) were based on data collected in nine regions which did not cover the entire country, in contrast to the SSP. The period being considered and the sampling depths (0–5 cm under grassland, 0–25 cm under cropland) also differ from our study. These differences might explain why the results reported in Tables 3 and 4 do not confirm the slight increase in SOC content indicated by Reijneveld et al. (2009): a significant decrease in mean SOC content in the 0–30 cm layer in mineral soils is shown for cropland, and changes could not be shown for grassland.

5. Conclusions

The aim of this paper was to present the changes in SOM content, SOC content and SOC stock between 1998 and 2018. We conclude as follows (all conclusions based on a 5% significance level):

1. The mean SOM content in the entire area of interest (non-built-up area in the Netherlands) changed significantly in the 30–100 cm layer between 1998 and 2018 (decrease of 17.68 $\mathrm{g\,kg^{-1}}$).
2. A significant decrease in mean SOM content in the 0–30 cm layer could be shown in mineral soils under cropland by classmatching (-3.80 $\mathrm{g\,kg^{-1}}$). For the remaining domains of interest, changes could not be shown, either by classmatching or geomatching.
3. The different results indicate that the choice between geomatching and classmatching is relevant. This choice should depend on the type of information required. Classmatching is appropriate if accurate estimates of changes in mean contents and stocks are needed for a specific soil class, such as mineral soils. Geomatching can be chosen if map units of the soil map are used as administrative units for which changes in mean contents and stocks need to be monitored, for example to evaluate the effectiveness of policy.
4. Classmatching indicated that the mean SOM content in the 30–100 cm layer in mineral soils under cropland and grassland decreased significantly, by 8.59 and 4.75 $\mathrm{g\,kg^{-1}}$, respectively. It should be noted, however, that according to the Dutch system of soil classification, organic layers may be present in mineral soils at depths greater than 40 cm.
5. Assuming that the coefficients of the PTFs to predict soil bulk density (Wösten, 1997) are constant in time, calculations indicate that SOC stocks decreased in the 0–30 cm, 30–100 cm and 0–100 cm layers of mineral soils under both cropland and grassland in the Netherlands between 1998 and 2018. Inference in terms of statistical significance is not possible, however, because not all uncertainties related to the soil bulk density data could be quantified. If SOC stock changes are monitored for layers of fixed depths, for example 0–30 cm, we emphasize that the accuracy of soil bulk density data needs to be improved and quantified in future measurements, to obtain more accurate estimates of emissions from mineral soils under agricultural land and to enable inference in terms of statistical significance.

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. Estimation for groups of strata (geomatching)

The spatial mean of variable z in stratum h is estimated by

$$\hat{\bar{z}}_h = \frac{1}{n_h}\sum_{i=1}^{n_h} z_{hi} \tag{A.1}$$

where n_h is the number of sample locations in the hth stratum, and z_{hi} the ith observation of z in the hth stratum.

The variance of the estimator $\hat{\bar{z}}_h$ is estimated by

$$v(\hat{\bar{z}}_h) = \frac{1}{n_h(n_h-1)}\sum_{i=1}^{n_h}(z_{hi}-\hat{\bar{z}}_h)^2 \tag{A.2}$$

The spatial mean of a variable z in a group of H strata is estimated by

$$\hat{\bar{z}} = \sum_{h=1}^{H} a_h\cdot\hat{\bar{z}}_h \tag{A.3}$$

where a_h is the relative area of stratum $h, h = 1, \cdots, H$.

The variance of the estimator $\hat{\bar{z}}$ is estimated by

$$v(\hat{\bar{z}}) = \sum_{h=1}^{H} a_h^2\cdot v(\hat{\bar{z}}_h) \tag{A.4}$$

The effective number of degrees of freedom, needed in t-tests, is approximated by Satterthwaite’s method:

$$\nu_e = \frac{\left(\sum_{h=1}^{H} A_h^2 s_h^2\right)^2}{\sum_{h=1}^{H}\frac{A_h^4 s_h^4}{n_h-1}} \tag{A.5}$$

where A_h is the area, s_h^2 the estimated variance, n_h the number of sampling units in the hth stratum, and H the number of strata (Cochran, 1977).

Appendix B. Estimation for domains (classmatching)

A sub-area that does not coincide with the strata within a group of H strata is referred to as a 'domain of interest', or more briefly a 'domain'. To estimate the spatial mean of variable z in a domain, two ancillary variables are defined: z' and x, which equal z and 1, respectively, at any location within the domain, but are zero elsewhere. The mean of variable z within a domain D is estimated by the ratio of the means of z' and x:

$$\widehat{\bar{z}}_{\mathrm{D}} = \frac{\widehat{\bar{z}}'}{\widehat{\bar{x}}} = \frac{\sum_{h=1}^{H} a_h \cdot \widehat{\bar{z}}'_h}{\sum_{h=1}^{H} a_h \cdot \widehat{\bar{x}}_h} \tag{B.1}$$

where $\widehat{\bar{x}}$ is the area fraction of domain D, and $\widehat{\bar{z}}'_h$ and $\widehat{\bar{x}}_h$ are estimated analogous to $\widehat{\bar{z}}_h$ in Eq. A.1.

The variance of the estimator $\widehat{\bar{z}}_{\mathrm{D}}$ is estimated by

$$v\left(\widehat{\bar{z}}_{\mathrm{D}}\right) = \frac{1}{\widehat{\bar{x}}^2} \cdot \sum_{h=1}^{H} \frac{a_h^2}{n_h(n_h - 1)} \cdot \sum_{i=1}^{n_h} \left(d_{hi} - \frac{1}{n_h} \cdot \sum_{i=1}^{n_h} d_{hi} \right)^2 \tag{B.2}$$

where $d_{hi} = z'_{hi} - \widehat{\bar{z}}_{\mathrm{D}}$ at the ith location in the hth stratum, $h = 1 \cdots H$ and $i = 1 \cdots n_h$. Note that the estimated area fraction $\widehat{\bar{x}}$ is used in Eq. B.2 because the domain of interest in classmatching is the real area of a specific soil type that was determined from soil profile descriptions made at the sample locations. This real area is unknown since the perfect soil map does not exist, but can be estimated from the sample. If domains are not defined on the basis of classmatching but result from an overlay procedure, then $\widehat{\bar{x}}$ in Eq. B.2 can be replaced by the known areal fraction $\bar{x}$. The effective number of degrees of freedom is approximated by Eq. A.5.

Appendix C. Differences in methods to determine SOC stock, 1998 vs. 2018

Table C1.

Table C1
Differences in methods to determine SOC stock, 1998 vs. 2018.

Method	1998	2018	Possible effect on estimated SOC stock change (2018–1998)
# Visited locations	1396	1152	Random effect (see Section 2.1).
Positioning	1:25,000 topographical map and ruler guide	GPS	Random effect (see Section 4.1).
Auger	Edelman auger, one aliquot	Gouge auger, five cores and mixed	Random effect (see Sections 2.2 and 4.1).
Augered layers	Horizons	Depth layers (0–30 cm and 30–100 cm)	Recalculation from horizons to depth layers by mass weighting (see Section 2.6), possibly a random effect (see Section 4.1).
Preparation for laboratory analysis	Dried at 40°C and sieved < 2 mm	Dried at 40°C and sieved < 2 mm	No effect.
SOM content measurement	Loss on ignition	Loss on ignition	No effect.
SOC content measurement	Not measured	Elemental C following dry combustion	No effect. To avoid possible bias, SOC content was calculated from 0.5× SOM content for both 1998 and 2018 (see Section 2.6).
Clay content	Field estimates by soil surveyors	Density fractionation	Possibly a systematic effect. Eliminated by using data from 2018 in estimation of soil bulk densities in both 1998 and 2018.
Loam content	Field estimates by soil surveyors	NIRS	Possibly a systematic effect. Eliminated by using data from 2018 in estimation of soil bulk densities in both 1998 and 2018.
M50 sand fraction	Field estimates by soil surveyors	NIRS	Possibly a systematic effect. Eliminated by using data from 2018 in estimation of soil bulk densities in both 1998 and 2018.
Soil bulk density	Pedotransfer functions (Wösten, 1997), SOM content data from 1998, texture data from 2018 to avoid systematic errors due to differences in measurement methods between 1998 and 2018	Pedotransfer functions (Wösten, 1997), data from 2018	Possibly a systematic effect due to changed density over time, which was not accounted for.

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