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Monitoring soil organic matter on grassland farms: An exploratory analysis

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ABSTRACT

To meet the goals of the Climate Agreement, policy makers consider incentivizing soil carbon sequestration by carbon credits to offset greenhouse gas emissions from agriculture, industry and other sectors. Therefore, the interest in monitoring soil organic matter dynamics is growing rapidly, yet factors affecting the precision of the monitoring results are rarely quantified. We used the rhetorical scheme "The seven circumstances" to structure the methodological aspects of setting up a soil organic matter (SOM) monitoring program. The rhetorical scheme was applied during four years on two grass-based dairy farms in the Netherlands to assess in detail: conversion of SOM weight concentrations to SOM stocks (HOW), the effect of soil depth and the integration of scales field vs. farm (WHERE), and the effect of sampling date and sampling frequency on SOM estimates (WHEN). We found that all three circumstances affect conclusions on SOM stocks or SOM dynamics strongly. Considerable variation was found in the relationship between soil bulk density and SOM weight concentration (i.e. pedotransfer curves) among fields, depth and literature reference equations. Therefore, preferably a site specific pedotransfer curve should be used when comparing SOM stocks based on SOM weight concentrations across sites. Large differences in trends of SOM stock changes over time were found between fields and sampling depths. We conclude that a sampling depth in grassland soils up to 60 cm may be relevant to capture the dynamics in deeper layers. Furthermore, for quantitative underpinning of carbon payment schemes, the whole farm should be monitored rather than a few fields as trends between fields are highly variable.

1. Introduction

The public interest in soils is growing rapidly: a recent parliamentary letter of the government of the Netherlands states that maintaining soil quality is eminent to find solutions for multiple challenges society is facing such as climate change and water pollution (Government of the Netherlands, 2019a). Today, no national policy framework or agreement on soils exists. Although it is acknowledged that maintaining soil quality levels is an important condition for complying with the UN Climate agreement, the EU Water Framework Directive and the EU Nitrates directive, the ambitions in the national soil policy document are rather vague and not yet quantified. With the recent adoption of the 'no-debit rule' to compensate for emissions associated with land use by equivalent amounts of CO_2 removal, the Netherlands must improve land use management strategies to increase CO_2 absorption in agricultural and forest soils, because today the Land-use, Land-use change and Forestry (LULUCF) sector is still a net source of greenhouse gas emissions. In 2017, the annual net emissions from this category were 5.6 Tg CO_2 equivalents in the Netherlands (RIVM, 2019a). This should be reduced to zero emissions according to the 'no-debit rule'. The National Climate agreement of the Netherlands states that an additional amount of 0.5 Tg per year of CO_2 equivalents should be sequestered in agricultural lands (Government of the Netherlands, 2019b).

Policy makers ask scientists, advisors and farmers explicitly to operationalize goals of sustainable soil management and to deliver indicators for monitoring soil quality (Government of the Netherlands, 2019a). Especially, monitoring of soil organic matter (SOM) is of interest as this is a crucial factor to comply with the 'no-debit' rule. Regional governments are even considering incentivizing farmers for carbon sequestration (e.g. the Province of Friesland (2019) in the North of the Netherlands) proposes to pay farmers € 30 per ton CO_2 that is sequestered.) This is challenging as SOM stocks (commonly expressed in Mg

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(tonnes) of SOM ha^{-1}) are characterized by high levels of spatial heterogeneity and management induced changes in SOM are relatively small as compared to the SOM stock (Goidts et al., 2009; Fornara et al., 2020). Another complicating factor is that the requirements for setting up such a soil monitoring program are not clearly defined. A cacophony of monitoring advices is available prescribing to use different indicators, analytical methods, sampling designs and to sample different soil layers all depending on the scale and time period in which monitoring should take place (e.g. De Gruijter et al., 2006; Goidts et al., 2009; Hoogsteen et al., 2015; FAO, 2019). Different stakeholders have different questions, expecting different answers which vary in spatial and temporal resolution and every monitoring scheme yields another answer, so a careful selection of methods has to be made in relation to the purpose.

1.1. Current SOM measurements and results in the Netherlands

In the Netherlands, soil quality and agricultural production levels are generally high (Reijneveld, 2013). Recently, concerns were raised about declining soil quality and specifically, the quantity of SOM: farmers fear that SOM levels are declining as a consequence of increased stringency in the application rates of animal manure to their fields (PBL (Environmental Assessment Agency of the Netherlands), 2019). Trends at national level show that the SOM content of grasslands remained stable (Fig. 1). For arable land the SOM content tended to increase (n.s.) and under fields of silage maize no changes in SOM content have been observed (Fig. 1). However, information on SOM in grasslands is only available for the topsoil (0–10 cm).

1.2. Rhethorical scheme to set up a soil monitoring system

A number of factors need to be considered prior to setting up a monitoring system. This can be done in a structured way through the application of the rhethorical scheme "*The seven circumstances*" (after the Greek rhetoric Hermagoras of Temnos, as described by Robertson, 1946). Seven questions are central to this scheme: 1.Who, 2. What, 3. Where, 4. When, 5. How, 6. Why, 7. By what means. In the context of soil monitoring for SOM, the main objective is to quantify accurately the stocks of SOM and the development thereof in time. In Fig. 2, we provided a number of answers for all '*Circumstances*'. In the present study "Who" are the information requestors, the policy makers and farmers. The answer to the "What" question is: information on the stocks of soil organic matter and their trends. The aspects 6 and 7 are beyond the scope of this paper. The aim of this paper is to gain quantitative insights into the circumstances "How", "Where" and "When" for measurements of soil organic matter stocks in grasslands and the development of SOM stocks in time, in order to answer the questions of the requestors. Through intensive soil monitoring on two dairy farms we explore the effects of different approaches to derive data on stocks of SOM from measurements of the mass concentration of SOM (How), the effect of the sampling depth, the integration level of the data (field or farm), (Where), and the effects of seasonality (When) on the quality of the reported data.

2. Materials & methods

2.1. Farm characteristics and grassland management

The farms were located in "De Gelderse Vallei" which is a sub-region in the center of the Netherlands (province of Gelderland). From March 2010 to January 2014, 14 grassland fields were monitored on two farms (7 fields per farm). The farms are located on sandy soils in "Het Binnenveld" (Farm A, 51° 99′ 72.79″ N; 5° 62′ 18.84″ E) and Lunteren (Farm B, 52° 08′ 95.46″ N; 5° 59′ 07.35″ E) and are about 10 km away from each other. The clay content (fraction ≤ 20 μm) of the 7 fields from Farm A and Farm B ranged from 69 to 127 g kg^{-1} and 41 to 64 g kg^{-1}, respectively. Due to the geological history of the area, which is on the southern edge of the ice sheet of the Saalian Ice Age, the soil profiles in the area are, especially around Farm A, highly variable. The SOM content of all farm grasslands was monitored during the four years with a three monthly sampling interval at three different layers: the 0–10 cm, 10–30 cm and 30–60 cm soil layers. Samples were collected in the first month of each season (spring, summer, autumn and winter).

2.1.1. Farm A – De Hooilanden

The field size varied from 1.2 to 4.0 ha. A map of the farm and the sampled fields is shown in Fig. 3. Historically the farmlands were referred to as hay lands (in Dutch: De Hooilanden) because the soil was too wet for other agricultural purposes (Oosting, 1936). In the 14th century, the area consisted of peat swamps that disappeared after the peat harvesting in the middle ages. A sandy cover soil remained. In the 18th century, the area was mainly used for livestock production. In the fields monitored in this study, some peat fragments were observed only

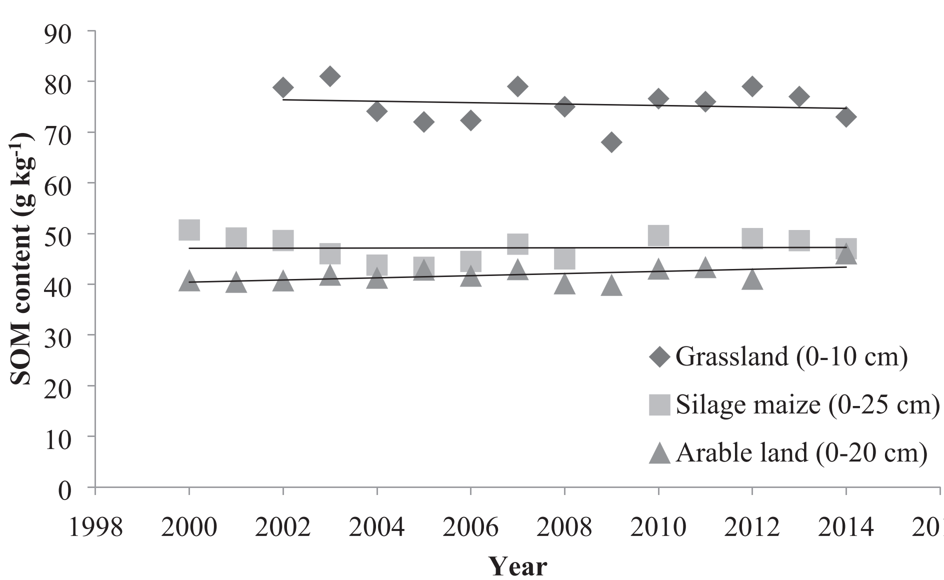

Fig. 1. Trends in soil organic matter (SOM) content for different land-use categories in the Netherlands (PBL, 2019).

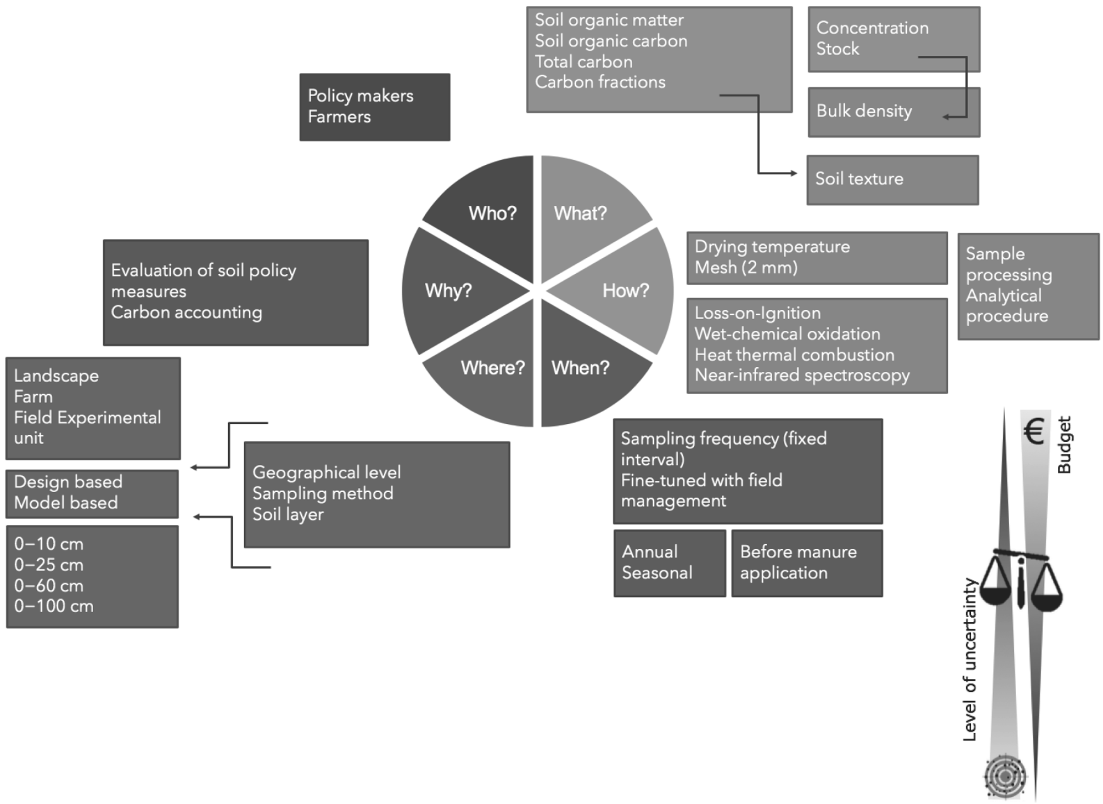

Fig. 2. Answers to the seven 'circumstances' in the context of setting up a soil organic matter monitoring program for grasslands. A balanced choice should be made aiming to reduce the level of uncertainty as much as possible within the available budget ("By what means").

Fig. 3. Location of the sampled fields (Field 1–7) of Farm A, "De Hooilanden" in Bennekom, the Netherlands. See the text for details. General details about the farm management are presented in Table 1. Characteristics at field level are provided in Table 2.

in the subsoil layer on the North West side of the farm (field 5). The subsoil of the other fields was sandy. Farm A has been under organic management since 2003 and employed a pasture based lenient strip stocking system. This system uses movable fences and cows are put to graze in long standing biomass. Every three hours the stocking area is enlarged by moving the fence except for the night when the fence is moved after a period of six hours. Data on the stocking density etc. are given in Table 1. The system employed on farm A aims at minimizing the use of concentrates and synchronizes grass demand with supply by spring calving. The stocking density was 2.5 dairy cow per hectare as can be derived from Table 1. The annual dry matter yield of the grasslands was estimated to be 6 Mg DM ha^{-1}. The cattle diet consisted of mainly forage (grass/clover) and was supplemented with maize and triticale. All cattle were housed in a cubicle stable and cattle slurry was the main manure type produced on the farm. Some solid farmyard manure was also produced during the calving period because at that time the calving cows were housed in a deep litter stable. In 2012 solid cattle manure was applied once to fields 6 and 7 at a rate equivalent to 7 m^3 ha^{-1} yr^{-1}. Every year in early spring (March) all fields were fertilized with cattle slurry (CS; 25 m^3 ha^{-1}) and an additional application of CS followed in July and August (15 m^3 ha^{-1}). The stocking management was identical across the fields as the herd was quickly rotated over the farm. Every field was grazed seven times during the growing season. The total number of grazing days was about 240 days per year, in the period April – November. The fields close to the homestead were used mainly for night grazing (fields 1–3), while the fields further away (4–7) were used for day grazing. In 2010, fields 1–6 had been under grass for at least 20 years and field 7 since 2003. The main grassland species on the farm were perennial ryegrass (*Lolium perenne* L.), orchard grass (*Dactylis glomerata* L.), white clover (*Trifolium repens* L.) and red clover (*Trifolium pratense* L.).

2.1.2. Farm B – De Groote Voort

De Groote Voort has been managed by the family Van der Voort for over four centuries and is under organic management since 1992. The farmer employs the modern continuous stocking systems and the

Table 1
Characteristics of the soil and grassland management of two farms on sandy soils in "de Gelderse Vallei", the Netherlands, at the start of the monitoring period (Spring 2010). The silt + clay content (SC) is expressed in g kg^{-1} soil. The SOM content is given in Mg ha^{-1}. Standard errors of the mean are given between brackets. CS = cattle slurry, SCM = solid cattle manure. The amounts of applied manure are expressed in Mg OM ha^{-1} yr^{-1}.

	Farm A		Farm B	
No. of fields sampled	7		7	
Soil layer	SC (g kg^{-1})	SOM (Mg ha^{-1})	SC (g kg^{-1})	SOM (Mg ha^{-1})
0–10 cm	97 (7)	65 (3)	59 (3)	60 (3)
10–30 cm	98 (8)	108 (6)	57 (3)	74 (4)
30–60 cm	88 (7)	126 (11)	52 (2)	64 (7)
Livestock type	Whitehead		Jersey	
Herd size (no. of dairy cows)	74		85	
Grassland area of the farm (ha)	30		32	
Stocking system	Lenient strip		Continuous	
Average age of the grassland (years)	18		25	
Type and amount of applied manure from dairy cows (Mg OM ha^{-1} yr^{-1})[b]	CS: 2.9		CS: 0.7	
	SCM: 0 or 1[a] During grazing: 1.7 Total: 4.6 or 5.5		SCM: 2.1 During grazing: 1.6 Total: 4.4	

[a]SCM was applied every year to two out of seven fields, thus each field received manure once every four years. The amount was 1 Mg OM ha^{-1} which is equal to 0.25 Mg OM ha^{-1} yr^{-1} (1 Mg OM ha^{-1} per 4 years). The application of SCM rotated over the fields.
[b]See the Supplementary material, Box S1 for details on the calculation.

grazing season lasts from April to the beginning of November. In this system, cattle are quickly rotated over the parcels and graze a few hours on each field every day. The field size varied from 2.4 to 4.3 ha. In February and August all fields were fertilized with respectively, 12.5 and 2.5 m^3 solid cattle manure per hectare. In March 10 m^3 of cattle slurry per ha was applied to all fields. The diet of the cows consisted of fresh forage and triticale, supplemented with a mixture of herbs, dried fruits, nuts, and minerals. Fig. 4 shows the location of the sampled fields.

In 2010, fields 1–5 had been under permanent grassland for a period of 23–25 years. Before that time, the fields were in grass/maize rotation. The botanical composition consisted of perennial ryegrass (*Lolium perenne* L.), white clover (*Trifolium repens* L.), and dandelion (*Taraxacum officinale*). Cuckooflower (*Cardamine pratensis* L.) and common daisy (*Bellis perennis* L.). Creeping thistle (*Cirsium arvense*) also occurred on the grasslands.

About forty years ago, a horse riding school was established on the front side of field 6. The back of the field was an orchard. After the closure of the riding school, the productivity of the field was extremely low and the area was used as storage area. In 2010 the field had been under grass for about 25 years and the botanical composition consisted of perennial ryegrass and white clover as the dominant plant species. The backside of the field was characterized by a variety of herbs and orchard grass (*Dactylis glomerata* L.). Field 7 was the most productive field about 40 years ago according to the farmer. Despite the great productivity, extension workers recommended the field to be deeply ploughed (ploughing down to a depth of 60 cm) in the 1980's for unknown reasons. After ploughing, grass was grown in rotation with maize. About 12 years ago, the field was renovated and a mixture of perennial ryegrass and white clover was sown.

The total number of grazing days was about 200 days per year in the period April–November.

Weather data was obtained from a local weather station of Wageningen University & Research centre which was about 1 km away from Farm A and 15 km away from Farm B. Between 2004 and 2014, the average yearly temperature was 10.4 °C and the annual precipitation sum was 859 mm.

2.2. *Sample collection and analytical procedures - "How"*

Sampling took place four times per year for a period of four years (Spring 2010 – Winter 2014; the average sampling interval was 89 days). All fields were sampled systematically in a zigzag pattern and 40 subsamples per field were collected to obtain three composite samples, i.e. one per soil layer: 0–10 cm, 10–30 cm, 30–60 cm. Samples were stored in plastic bags and dried overnight at 105 °C. After drying, samples were crushed and sieved at 1.8 mm. The soil organic matter (SOM) content was determined by loss-on-ignition (LOI; 550 °C with an ignition period of three hours and a sample weight of 20 g (see Hoogsteen et al., (2015) for details on the method). The LOI method was chosen because of the smaller variation among pseudo-replicates as compared to SOC analysis procedures (Hoogsteen et al., 2015). The near-infrared method analysis was not a common practice at the start of the monitoring period in spring 2010 and was therefore not chosen for SOM analysis. Corrections were made for structural water losses by subtracting 0.075 × the clay fraction from the LOI measurements (Hoogsteen et al., 2015). The soil texture of all samples was determined through laser diffractometry (Beckman Coulter LS Particle size analyser, Woerden, the Netherlands).

In July 2013, to determine soil bulk density (BD) a soil pit was dug and cylindrical cores were pressed into the soil profile (ISO, 1998)) in the 0–30 cm soil layer (n = 6 per field) for each layer of 5 cm. In total 252 samples were collected per farm (6 layers × 6 sampling locations per field × 7 fields). The soil was carefully pressed out of the cores, collected in a paper bag and dried overnight at 105 °C. The SOM content was determined in every BD sample (through LOI, see above) to derive for both farms a relationship between bulk density and SOM. The bulk density in the 30–60 cm soil layer was not determined.

2.3. *Data processing and statistical analyses – "How"*

2.3.1. *How to derive SOM stocks from SOM weight concentrations.*

Carbon credits are commonly expressed in tonnes of CO_2 equivalents. If the carbon content of SOM is taken to be 51% (Pribyl, 2010) and the carbon content of CO_2 = 12 / 44 = 27%, 1 ton SOM is approximately 2 ton CO_2 equivalents. When laboratory measurements for soil organic matter (SOM) are conducted a mass concentration is reported in g SOM kg^{-1} soil. Using the soil bulk density (kg m^{-3}), these concentrations can be converted to volume concentrations (kg SOM m^{-3}) or SOM stocks (kg SOM ha^{-1}). BD measurements are labor intensive and for this reason generic pedotransfer functions or even fixed values are used (e.g. BD is only measured at the start or end of an experiment). It is to be expected that the effect of different BD functions on SOM stock changes on the same field in time will be smaller than on the absolute amounts of SOM stocks, but the size of both effects is unclear. Therefore, we examined the effect of different pedotransfer functions describing the relationship between the BD and SOM weight concentrations.

Per farm three models depicted as curves were derived from the data:
(a) A curve including all data points from the farm.
(b) A curve representing the lower limit of all BD/SOM data points.
(c) A curve representing the upper limit of all BD/SOM data points.

Six pedotransfer functions (three per farm) were derived for the relationship between BD and the SOM weight concentration:

$$BD = \alpha \cdot e^{-\beta \cdot SOM} \quad (1)$$

Where: BD = soil bulk density in g cm^{-3} SOM = the soil organic matter concentration in g SOM kg^{-1} soilα (g cm^{-3}) and β (kg g^{-1}) are the regression coefficients.

Fig. 4. Location of the sampled fields (Field 1–7) of Farm B, "De Groote Voort" in Lunteren, the Netherlands. See the text for details. General details about the farm management are presented in Table 1. Characteristics at field level are provided in Table 2.

For the average curves all data points are included to derive the equations. For the upper and lower limit curve, data points were divided in 'bins' of equal distances (of increasing SOM content, i.e. Bin 1: 0–10 g SOM kg^{-1} soil; Bin 2: 10–20 g SOM kg^{-1} soil etc.; Cade & Noon, 2003). Of each bin the highest and lowest BD values were taken. Next, the six pedotransfer functions were applied to the SOM weight concentrations measured on the two farms and their fields. The estimated BD value and the SOM weight concentration were used to calculate the SOM stock:

$$SOM\,stock\,(Mg\,ha^{-1}) = soil\,layer\,(cm)\cdot 10^{8}\,(cm^{2}ha^{-1})\cdot\alpha\cdot e^{-\beta\,SOM}(g\,cm^{-3})\cdot 10^{-6}(Mg\,g^{-1})\cdot SOM(g\,kg^{-1})\cdot 10^{3}(kg\,Mg^{-1})\cdot 10^{-6}(Mg\,Mg^{-1}) \quad (2)$$

The three curves (i.e. All data points, BDmin and BDmax) were applied to the SOM weight concentrations at $t = 0$ and for each farm-soil layer combination. Analysis of variance was conducted with SOM stock as the dependent variable and BD curve as factor (i.e. All data points, BDmin and BDmax), (LSD or Dunnett's T3 in the case of unequal variances, $P < 0.05$). The statistical analysis for assessing SOM stock change over time is presented below (see section "Where?" – Analysis at farm and field level for different soil layers). SPSS (24th edition) was used to perform the statistical analyses.

2.3.2. Pedotransfer curves from the literature

The Google Scholar abstract database (in English) and Google search engine (in Dutch) were used to find reported relationships between BD and SOM. The search terms were: soil bulk density, relationship and soil organic matter. In Dutch the same search terms were used (i.e. bodemdichtheid = soil bulk density; relatie = relationship; bodem organische stof = soil organic matter). The criterion for inclusion was the presentation of individual data points on both BD and SOM weight concentration. This resulted in three studies in English and three studies in Dutch. Data was taken from the tables or from the graphs using WebPlotDigitizer (Automeris, 2019). An overview of the curves obtained from the literature, for the two farms of the current study and the ranges in BD and SOM is presented in Table 3. Furthermore, the equation used by Eurofins Agro, (one of the largest soil laboratories in the Netherlands), to convert SOM weight concentrations to SOM stocks in sandy cover soils, is also given in this table. Note, Farms A and B are located on sandy cover soils.

2.3.3. SOC stock analysis at farm and field level and for different soil layers - . "Where?"

In total 672 samples were collected (two farms × seven fields × three soil layers × 16 sampling dates). SOM weight concentrations were converted to SOM stocks using Equation 2 (farm specific curves, including all data points per farm). The SOM stocks from the 0–30 cm and 0–60 cm soil layers were obtained by summing up the stocks of the 0–10 cm and 10–30 cm soil layers, and all sampled layers, respectively. SOM stocks (Mg ha^{-1}) were plotted against time. Values that were outside 1.5 times the interquartile range were considered as outliers (Tukey, 1977). Eleven out of 672 observations were removed as outliers (five measurements from Farm A and six from Farm B). Normality was assessed with the Shapiro Wilk test (data not presented).

Statistical analysis was conducted at farm level and at field level. SOM stock levels at the farm scale were obtained by multiplying the SOM stock of each field with the field size divided by the total sampled area (see Table 2 for the field sizes). Trends in the stock of SOM over time were estimated for each farm-soil layer combination using ordinary linear regression (soil layers: 0–10 cm, 10–30 cm, 30–60 cm, 0–30 cm, 0–60 cm), in 2 farms × 5 soil layers = 10 analyses. The SOM stock was the dependent variable and time was the independent variable. At field

Table 2
Characteristics of each field. The size, silt + clay content and age of the grassland is given. Other relevant details concerning the (former) management of the fields are also provided. N.A. is not applicable: in those cases no other details were worthwhile mentioning.

			Silt + clay content (fraction < 20 µm)				
Farm	Field	Field size (ha)	0–10 cm	10–30 cm	30–60 cm	Age of the grassland in 2010 (years)	Other details
A	1	3.0	11.8	12.7	9.9	>20	Day + Night grazing
	2	4.0	8.2	8.4	7.6	>20	Day + Night grazing
	3	4.0	9.8	9.5	10.0	>20	Day + Night grazing
	4	1.6	10.4	10.0	6.6	>20	Day grazing Some peat fragments in subsoil
	5	1.2	10.4	10.6	10.5	>20	Day grazing
	6	4.6	7.5	7.4	6.5	>20	Day grazing SCM application in 2012
	7	3.6	6.9	7.2	7.8	7	Day grazing SCM application in 2012 Also used as stocking area for young stock
B	1	3.4	4.1	4.1	3.9	23–25	N.A.
	2	3.1	6.2	5.9	5.4	23–25	N.A.
	3	4.1	5.9	5.7	4.9	23–25	N.A.
	4	4.3	6.3	6.1	5.5	23–25	N.A.
	5	4.0	6.4	6.1	5.5	23–25	N.A.
	6	2.4	5.9	5.4	4.7	25	Land-use 30 years ago: horse riding school and orchard
	7	4.8	5.0	5.1	4.6	12	Deep-ploughing event in the 1980's

Table 3
Overview of the equations obtained for the two farms and from the literature for the relationship between the soil bulk density (BD) and the soil organic matter weight concentration (SOM). n.r. = not reported.

Study	Region and land-use	n	Range in BD (g cm^{-3})	Range in SOM(g kg^{-1})	Equation
This study, Farm A	NL – grassland	252	1.75–0.61	0–244	$BD = \alpha \bullet e^{-\beta \bullet SOM}$
This study, Farm B	NL – grassland	252	1.66–0.70	0–153	$BD = \alpha \bullet e^{-\beta \bullet SOM}$
Adams, (1973)	Podzolic soils	n.r.	1.64–0.24	0–1000	$BD = \frac{1000}{\left(\frac{SOM}{\alpha}\right) + \left(\frac{1000 - SOM}{\beta}\right)}$
Hossain et al. (2015)	Canada, Arctic region, forest soils and wetland	111	1.69–0.06	0–892	$BD = \alpha + \beta \bullet e^{-\beta \bullet SOM}$
Perie and Ouimet (2008)	Canada, Boreal forest soils	125	1.92–0.37	2–248	$BD = \alpha + \beta \bullet SOM - \gamma * \ln SOM - \varepsilon * (\ln SOM)^2$
De Haan and van Geel (2019)	NL – Unknown	20	1.47–0.86	10–200	$BD = \frac{1}{\alpha \bullet SOM + \beta}$
Zwart et al., (2013)	NL – Arable soils	20	1.45–0.20	28–950	$BD = \alpha \bullet \ln SOM + \beta$
Van Eekeren et al., (2018)	NL – Unknown	4	1.42–1.17	20–79	Not mentioned.
Eurofins Agro	NL – sandy cover soils	n.r.	1.53–0.78	0–250	$BD = \frac{1}{\alpha \bullet SOM + \beta}$

level the same analyses were conducted (2 farms × 5 soil layers × 7 fields per farm = 70 analyses).

2.3.4. Sampling frequency - "When?" –

The effect of sampling frequency on the estimated changes in stocks of SOM over time was assessed for a sampling frequency of four times per year, twice per year (spring and autumn; winter and summer) and once per year (spring, summer, autumn, winter). Ordinary linear regression was conducted using SOM stock as the dependent variable and time as the independent variable. Analyses were conducted for each farm-soil layer combination.

3. Results

3.1. Derivation of SOM stocks from SOM weight concentrations - "How"

Very strong relationships were found between the bulk density and soil organic matter weight concentrations (Fig. 5). Most variance was explained for the dataset with the maximum BD/SOM ratio's (BDmax) of Farm A (cf. $R^2 = 0.99$; Fig. 5a). Fig. 5c demonstrates that the curves of Farms A and B are within the range of other curves found in the literature.

SOM weight concentrations at the start of the monitoring period (t = 0, spring 2010) were converted to SOM stocks with the farm specific pedotransfer functions (cf. Fig. 5a and b). The BDmin curve resulted in the lowest calculated SOM stocks and the BDmax curve in the highest SOM stocks (Fig. 6; Table S3).

The SOM stocks calculated with the BDmin curve were on average 16% less than the SOM stocks based on the curve using all data points. SOM stocks based on the BDmax curve were on average 12% larger than the SOM stocks based on all data points (Supplementary material, Figure S1). Significant differences were found between SOM stocks calculated based on different pedotransfer curves derived from the monitoring activities described in this paper (Supplementary material, Table S3). However, note that the different pedotransfer functions do hardly affect the trends in SOM stocks (Fig. 7) which will be presented in the rest of this section.

3.2. Analysis at farm and field level for different soil layers - "Where?"

3.2.1. Farm level

In the 0–10 cm soil layer SOM increased with on average 1.2 (SE = 0.4, $P < 0.05$) and 1.1 (SE = 0.5, $P < 0.05$) Mg ha^{-1} yr^{-1} on Farm A and Farm B, respectively (Fig. 8). In the 10–30 cm soil layer SOM tended to decline on both farms with −1.2 (SE = 0.7) Mg ha^{-1} yr^{-1} (Farm A, P = 0.12) and −1.5 (SE = 0.8) Mg ha^{-1} yr^{-1} (Farm B, P = 0.07). In the 30–60 cm soil layer no change in SOM was observed on Farm A (0.7 (SE = 1.8) Mg ha^{-1} yr^{-1}, P = 0.71). On Farm B SOM tended to increase with

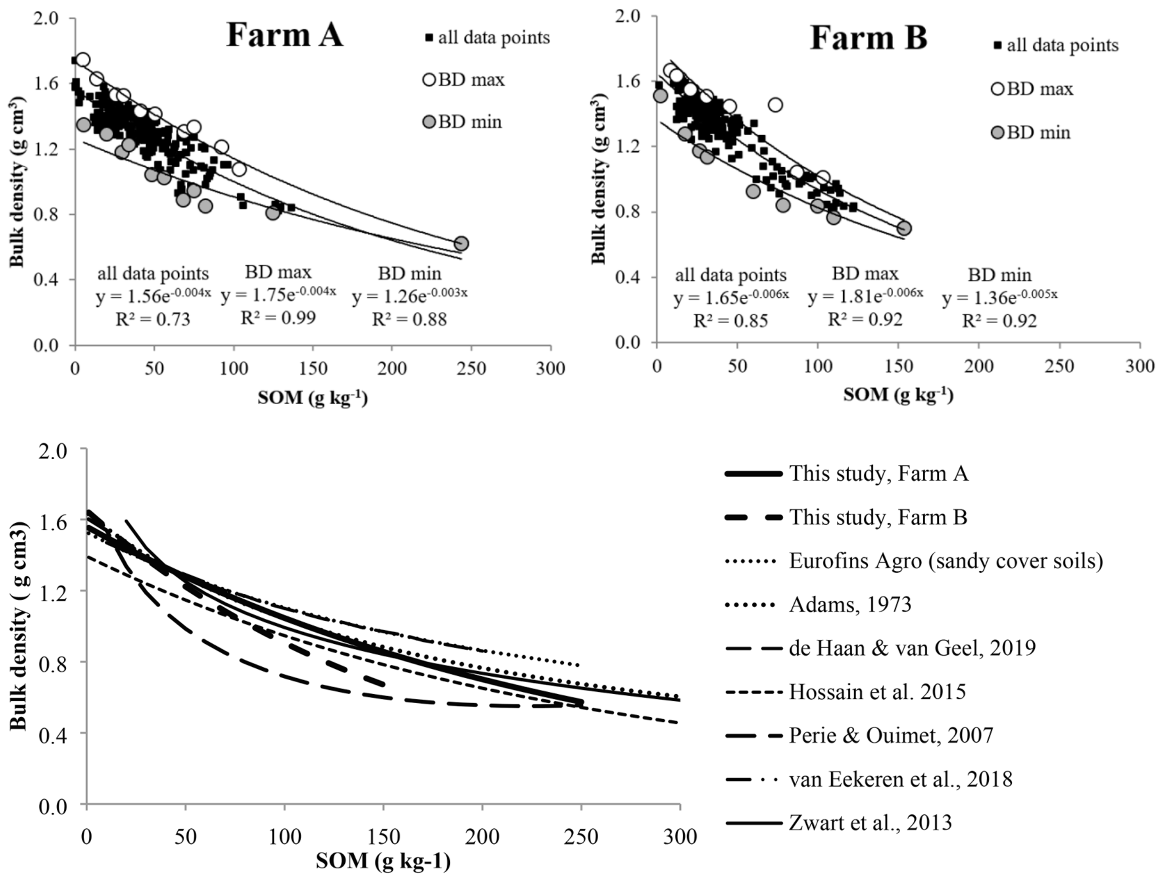

Fig. 5. Relationship between soil bulk density and soil organic matter (SOM) weight concentration for Farm A [a], Farm B [b] and a number of equations obtained from the literature [c]. In [a], [b]: the upper and lower curve (BDmax and BDmin, respectively) were derived from a subset of the data points (see Materials and methods). Details of the curves are provided in the supplementary material, Table S2. In [c] the curves of both farms based on all data points are given.

3.6 (SE = 1.7) Mg ha^{-1} yr^{-1} ($P = 0.06$). Large differences between farms were observed when considering changes in the entire sampled profile: the SOM stock in the 0–60 cm soil layer of Farm A remained stable (0.6 (SE = 2.1) Mg ha^{-1} yr^{-1}, $P = 0.77$) and on Farm B the SOM stock tended (non-significantly) to increase (3.1 (SE = 2.4) Mg ha^{-1} yr^{-1}, $P = 0.21$).

3.2.2. *Field level*

Large differences in SOM dynamics were found between fields, especially when considering the whole sampled soil profile (Fig. 9). In all fields of both farms, SOM tended to increase in the 0–10 cm soil layer, however, this was in most cases not significant. Greatest SOM accumulation rates in the 0–10 cm soil layer were found in field number 5 of Farm A (4.6 Mg SOM ha^{-1} yr^{-1}; $P = 0.02$) and Field 1 of Farm B (2.3 Mg ha^{-1} yr^{-1}; $P = 0.00$). In the 10–30 cm soil layer, two significant changes of SOM were found on Farm A (Fields 6 and 7). SOM tended to decrease in nearly all fields of Farm B (in Fields 3 and 6 significantly). In the 30–60 cm soil layer, no significant changes in SOM were found for Farm A. For Farm B, three out of seven fields showed a significant increase in SOM over time (Field numbers 1, 5 and 7).

3.3. *Sampling frequency – "When"*

A sampling frequency of twice per year (spring and autumn; winter and summer) showed trends that were similar to a sampling frequency of four times per year (Figs. 7 and 9). Yet, *P*-values were higher than the *P*-values obtained with a sampling frequency of four times per year. None of the trends at farm level with a sampling frequency of twice per year showed a significant change of SOM stocks over time (Fig. 10).

A sampling frequency of once per year (spring, summer, autumn or winter) showed no seasonal effect on SOM stock changes in the 0–10 cm soil layer at both farms (Fig. 11). In most cases SOM tended to increase or remained stable. In the 10–30 cm soil layer at Farm A, SOM remained stable in spring, summer and winter measurements. With autumn measurements a significant decrease in SOM was found. At Farm B, SOM tended to decline in the 10–30 cm soil layer, except for the summer measurements when SOM remained stable. In the 30–60 cm soil layer no changes in SOM were observed at Farm A for the different seasons. At Farm B, SOM increased significantly with spring measurements (30–60 cm soil layer; Fig. 11a). This was the case for all fields (Supplementary material, Figure S2). Overall, smallest changes in SOM over time were observed in winter measurements for all soil layers at both farms (Fig. 11d).

4. Discussion

We aimed to provide quantitative insights into the effects of sampling and analytical methods ("How") the spatial design of the sampling (farm vs field, "Where") and the temporal design of the sampling (time and frequency, "When") for measurements of soil organic matter stocks in grasslands and the development thereof in time through intensive monitoring of two dairy farms in the Netherlands. We found that all three circumstances affected conclusions on SOM stocks or SOM dynamics strongly. In the following sections we discuss the findings of this study for each circumstance separately.

4.1. *Derivation of SOM stocks from SOM weight concentrations - "How"*

The SOM weight concentration is of large influence on the BD as a

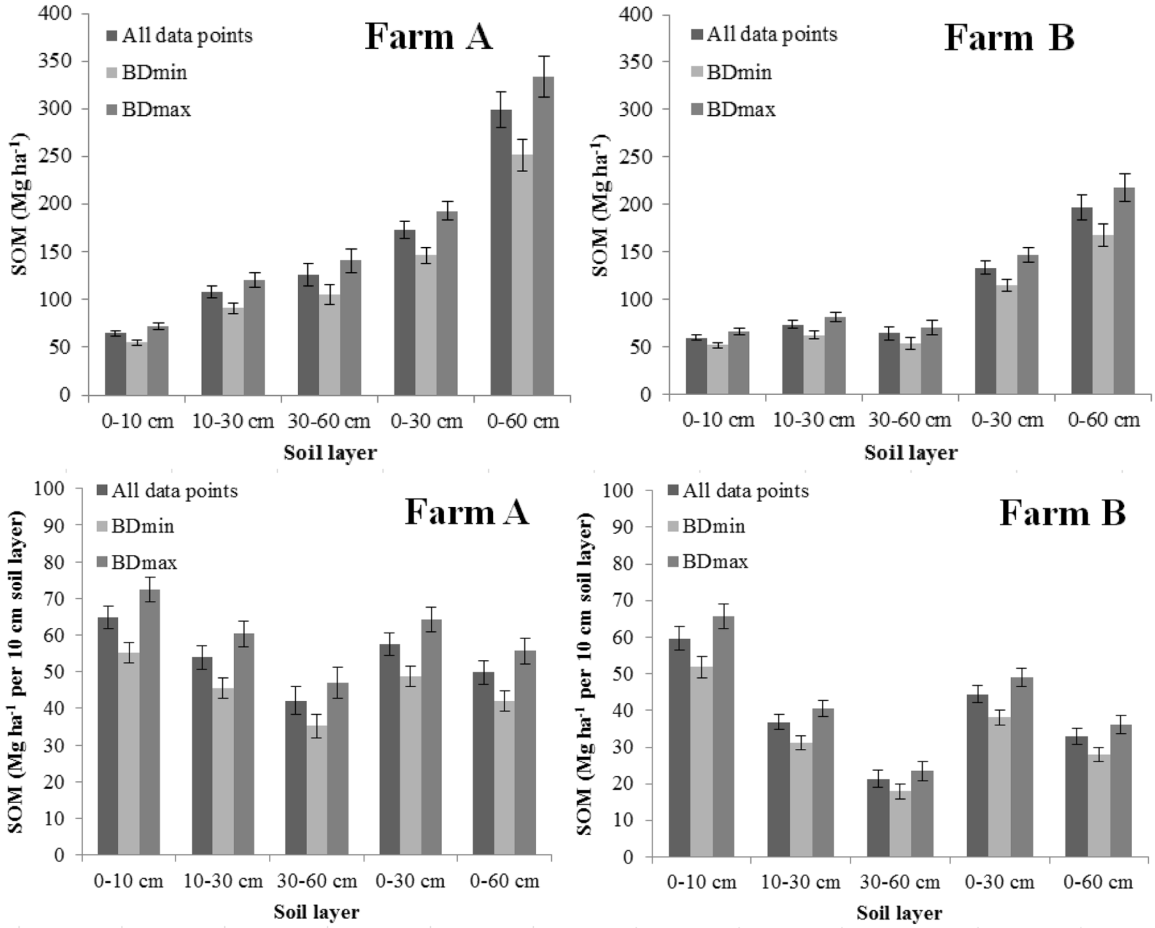

Fig. 6. Effect of different BD-SOM curves on the calculation of SOM concentrations to stocks for different soil layers at t = 0. Standard errors of the mean are presented. See Fig. 5a and b, and Table S2 for more details about the curves. The two upper graphs show cumulative total stocks for the three soil layers, and the two lower graphs show the stocks expressed per 10 cm soil layer.

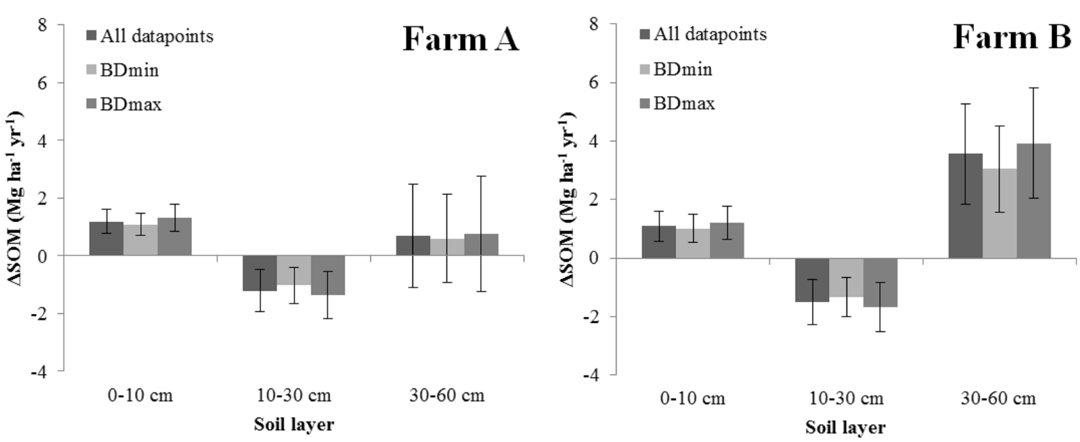

Fig. 7. SOM stock changes over time calculated with different pedotransfer (BD/SOM) curves. Standard errors are given.

consequence of large differences in specific weight between organic matter and the mineral fraction (Adams, 1973). Therefore, it is to be expected that significant differences are found between SOM stocks when different pedotransfer curves are used to convert SOM concentrations to SOM stocks. Comparison of different pedotransfer functions showed that the curves derived in this study were similar to the curves found in the scientific literature and some practical manuals (Fig. 5c). Yet, a significant effect of pedotransfer curve was found on the calculation of SOM stocks (Supplementary material, Figure S1). This is in accordance with the findings of De Vos et al. (2005) in their analysis of pedotransfer functions in forest soils.

In this study we assumed that the SOM weight concentration is the only variable influencing the soil bulk density. All other components in the soil such as the soil texture are presumed to be constant across different soil layers (NB. Table 2 shows little variation in soil texture levels between soil layers). In one soil core the vertical variation in soil

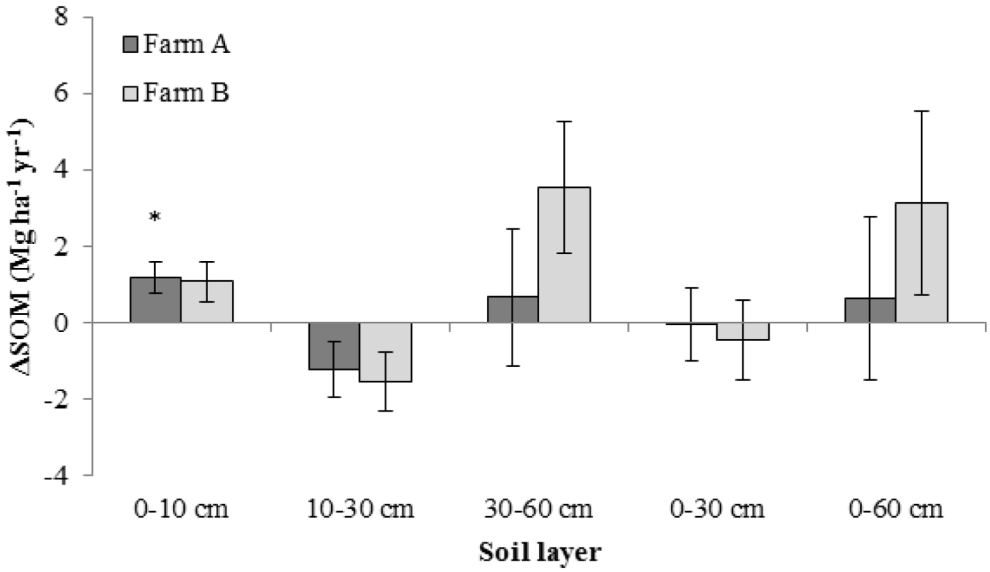

Fig. 8. Changes in soil organic matter (SOM) stocks over time for Farm A and Farm B per soil layer using a sampling frequency of four times per year. Standard errors are given. * indicates significance for slope values different from zero at $P < 0.05$.

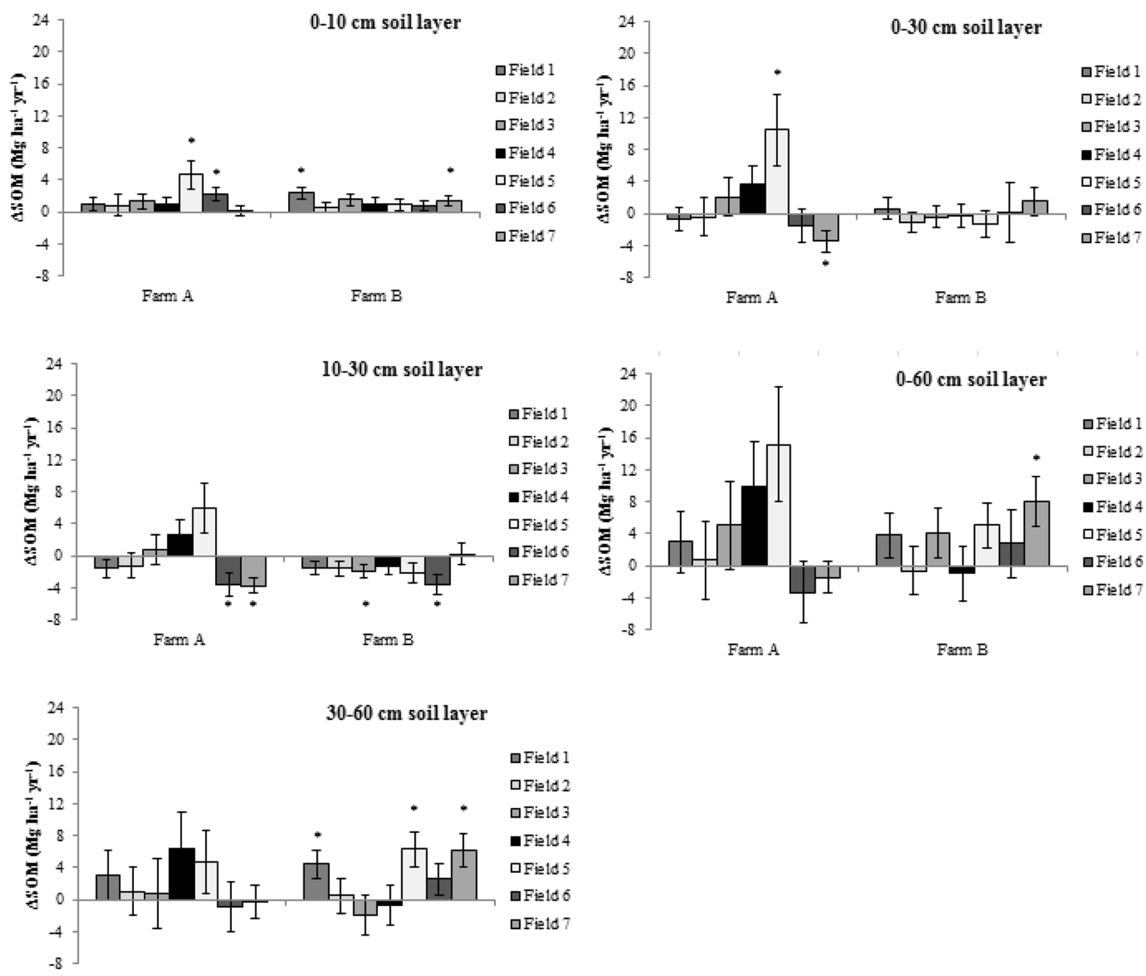

Fig. 9. Changes in soil organic matter (SOM) stocks over time for Farm A and Farm B per soil layer per field. Standard errors are given. * indicates significance for slope values different from zero at $P < 0.05$. Note the difference in scales with Fig. 8.

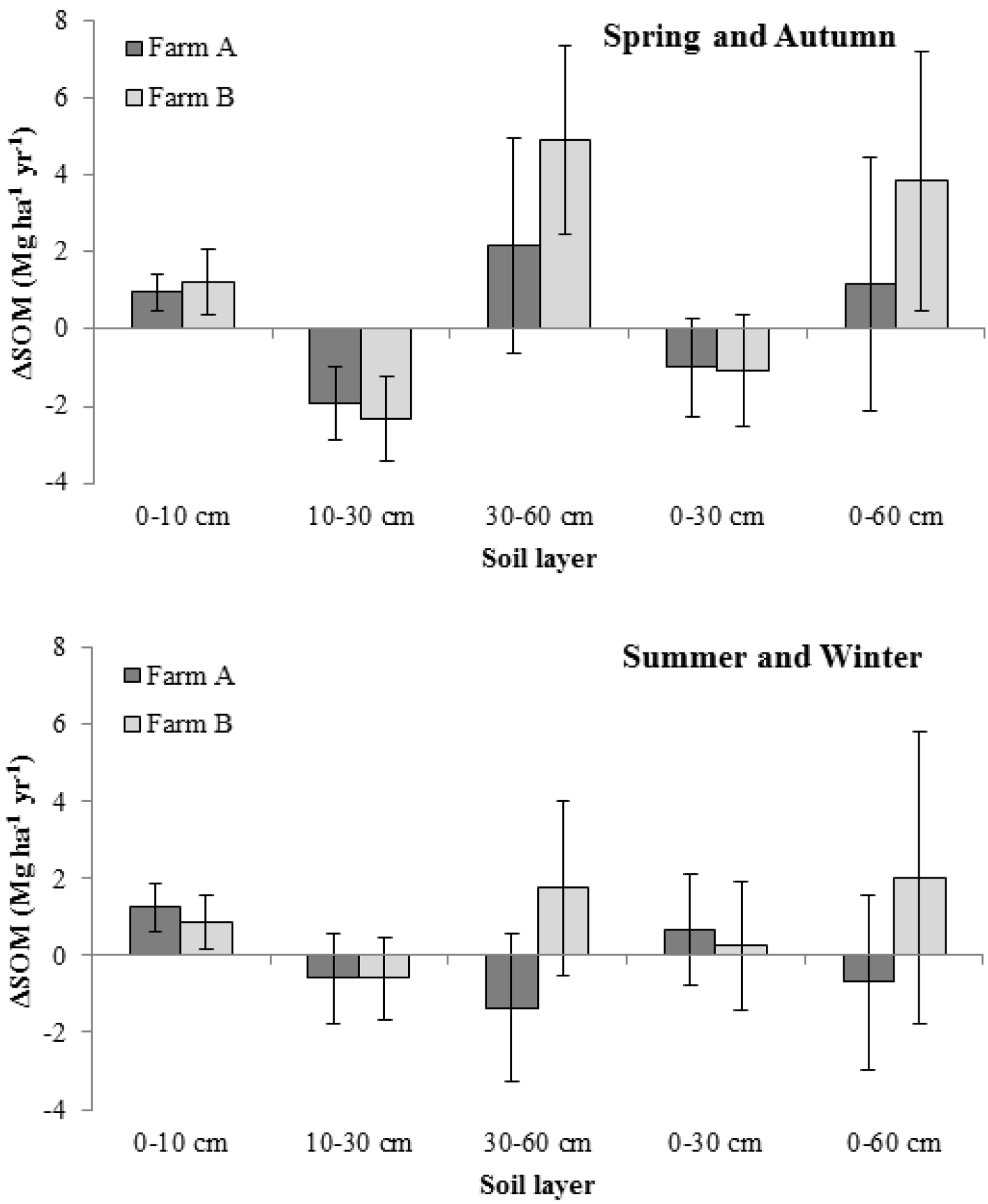

Fig. 10. Changes in soil organic matter (SOM) stocks over time for Farm A and Farm B per soil layer for a sampling frequency of two times per year. Standard errors are given. * indicates significance for slope values different from zero at $P < 0.05$.

texture was limited, however, the variation between soil cores from different fields was much higher. It is not expected that the shape of the BD curve (BD against the SOM weight concentration) depends strongly on the soil texture, as the specific gravity of sand is very similar to clay (sand: 2.7; clay: 2.6; Cabalar & Hasan, 2013). However, stoniness could be a major issue, leading to overestimations of SOM stocks (Poeplau et al., 2017). The method we used to convert SOM weight concentrations to SOM stocks is therefore only suitable for areas with unconsolidated soils without rock fragments, like most of the sedimentary soils in the Netherlands. For soils high in rock fragments, the current approach is only recommended when rock fragments are removed prior to determination of the soil mass (Poeplau et al., 2017). Note that in case rock fragments are not removed, voids that are filled with rocks are in reality filled with SOM free material, and not with soil, leading to incorrect estimations of BD values.

Although the type of BD curve (All data points, BDmin, BDmax) hardly influences conclusions on SOM stock changes over time, we argue that it is most accurate to use a pedotransfer curve based on site specific measurements of the bulk density rather than a (generic) curve from the literature, especially when SOM stocks are to be compared across different sites.

4.2. *Analysis at farm and field level for different soil layers - "Where?" –*

Large differences in SOM dynamics were found between farms, fields and depths (Figs. 7 and 8). In the 0–10 cm soil layer SOM increased on both farms (significantly at Farm A) and in the 10–30 cm soil layer, SOM tended to decline on both farms. This was attributed to the fact that SOM contents declined in the 10–20 cm soil layer (Don et al., 2009) and 10–30 cm soil layer (Hoogsteen et al., 2020) after the conversion from arable land to grasslands. Some of the grassland fields showed a decline in the SOM content, which was most probably related to management practices rather than land conversion (around 25 years ago), (0–30 cm soil layer, cf. Figs. 7 and 8). The increases in SOM in the 0–10 cm soil layer were fully compensated by decreases in the 10–30 cm soil layer, resulting in no net change for the 0–30 cm soil layer. Evidently, our results underpin that sampling depth is of crucial importance when monitoring SOM dynamics to draw conclusions on the sequestration

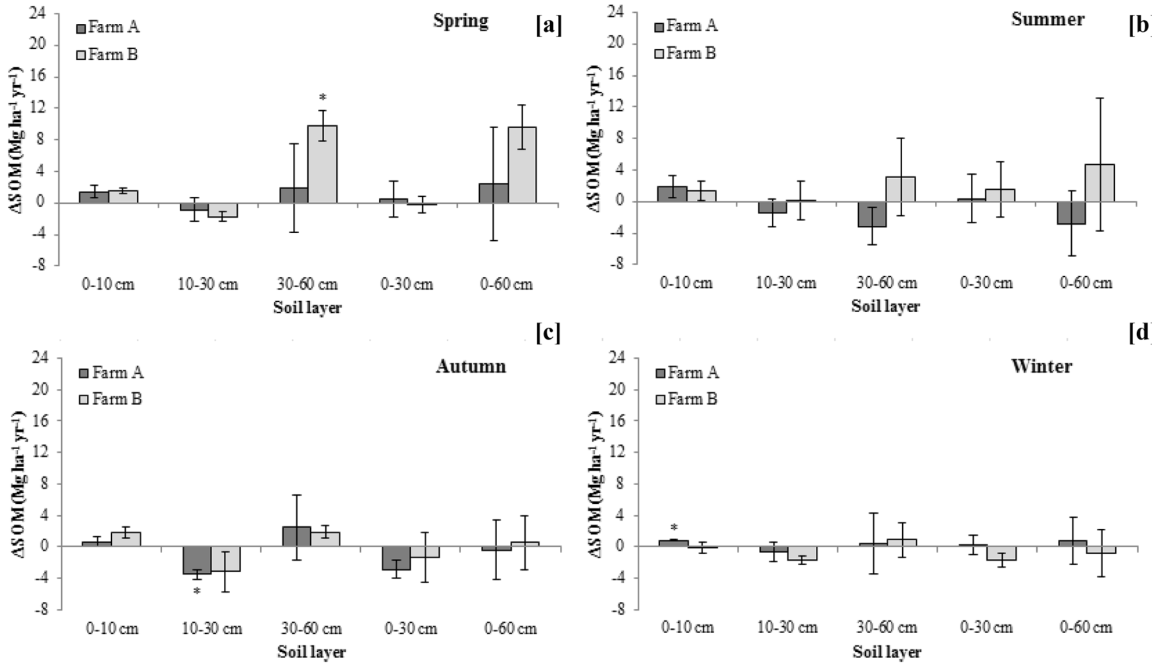

Fig. 11. Changes in soil organic matter (SOM) stocks over time for Farm A and Farm B per soil layer for a sampling frequency of once per year. Standard errors are given. * indicates significance for slope values different from zero at $P < 0.05$. Note the difference in scales with Fig. 10.

potential of grassland soils (cf. Taghizadeh-Toosi et al., 2014). Our grasslands did not sequester carbon as such, which is in contradiction with the 'rules of thumb' of Dutch farm advisors (e.g. van Eekeren et al., 2019). A recent practical handbook provided a number of measures to increase the SOM content on dairy farms: increasing the grassland age was mentioned as one of the best measures to do so. Large differences in SOM stock changes were found between farms for the 30–60 cm soil layer supposedly due to differences in (historical) management and drainage. On Farm A, no net change was observed and on Farm B, SOM tended to increase with 3.6 Mg ha^{-1} yr^{-1} (Fig. 8).

4.3. Sampling frequency - "When?"

The analysis at season level (sampling once per year) revealed that a significant increase in SOM stocks was only found when sampling in spring (Farm B and 30–60 cm); all fields of Farm B showed a consistent, significant increase of SOM in the 30–60 cm soil layer (Figure S2). The sampled farms show large differences between seasons which we could not explain, and which need further investigation. Based on a four-year intensive monitoring period it is not possible to disentangle the effects of sampling frequency and seasonal variation in SOM trends. A higher measurement frequency does not lead to finding a larger number of significant trends (Table S4). More insight is needed in the spatial variation of SOM in combination with detailed carbon balances at field level to determine a suitable sampling interval for assessing significant changes of SOM over time. For pragmatic reasons we recommend to sample once per year in winter because then we expect SOM inputs to interfere least with accuracy in SOM measurements (i.e. no soil compaction and trampling because stocking does not take place in winter and no manure input occurs (Fig. 11d)).

4.4. Differences between farms and fields

Possible explanations for the differences in SOM stock changes between farms are differences in manure and stocking management. Farm A employed a lenient strip stocking system, which is characterized by putting cows to graze in long standing biomass (about 20 cm). Some commercial farm enterprises claim multiple benefits of this system, including an increased level of soil carbon sequestration as compared to other stocking systems (Farmer's practice network: "Organic: climate neutral!", 2019). Although the grazing area of the cows is enlarged every three hours, the high livestock density (especially at the start of each day when the grazing area was smallest), results in large losses of herbage yield due to trampling and consequently extra C inputs into the soil. Annual net dry matter herbage yields were estimated to be roughly 6 Mg ha^{-1} which is low for Dutch production grasslands which commonly yield around 11 Mg ha^{-1} yr^{-1} (WEcR, 2019). Therefore, we presume that a large part of the produced biomass was not harvested leading to additional C input into the soil. This was not, however, reflected in higher SOM accumulation rates of Farm A as compared to Farm B, perhaps most likely because the additional SOM input was too small to be detected against a large and heterogeneous background SOM stock. According to Janssen (1984) about 20% of the added OM as green matter is still present in the soil after 1 year. Therefore, the annual additional input remaining after one year of application was estimated to be $0.2 \times (11–6) = 1$ Mg ha^{-1} yr^{-1}, against a background stock of around 65 Mg SOM ha^{-1} (SD = 8) in the 0–10 cm soil layer (note, soil sampling was not more difficult at Farm A, as the sward was much more open and the high biomass could be easily pushed to the side prior to putting the auger into the soil). The extra C flux did not occur on Farm B where grasslands were continuously stocked.

The average sward height on Farm B throughout the grazing season was about 8 cm and yield losses were considerably less than on Farm A: the annual net dry matter yield was estimated to be about 12 Mg ha^{-1} as confirmed by regular observations by the farmer (Personal communication with J.D. van der Voort, 2015). The difference in grass height also led to differences in clover content and consequently differences in soil life between both farms and thus decomposition rates of SOM (Rashid, 2013).

Van Eekeren et al. (2015) have shown a negative correlation between clover content and herbage height, which we also observed on the two farms, i.e. the clover content on Farm A was much lower than on Farm B. Furthermore, Van Eekeren et al., (2010) showed that the number of earthworms increased with increasing clover content, which was confirmed by observations on the same farms: Rashid (2013) found that the total number of earthworms and enchytraeids were, respectively, five and three times greater on the grasslands of Farm B (Field B2) than of Farm A (Field A3; Farm A and Farm B in this study were, respectively, Farm D and Farm B in the study of Rashid, 2013). The greater number of earthworms at Farm B as compared to Farm A possibly led to higher decomposition rates of SOM and more vertical transportation of SOM (through illuviation of for instance root exudates and mucilage; Jones & Donnelly, 2004). Soil displacement rates from earthworms (based on mounding) between 50 Mg ha^{-1} yr^{-1} were reported in the literature for non-tropical areas and bioturbation plays a key role in the carbon cycle (Wilkinson et al., 2009). The number of endogeic earthworms (which occur predominantly in the 10–15 cm soil layer; Van Eekeren et al. (2008) was four times larger on Farm B as compared to Farm A (304 per m^2 vs. 76 per m^2, Rashid, 2013). The difference in earthworm numbers and other biota (cf. Rashid, 2013) could be also related to the manure management. Large amounts of straw were imported at Farm B and most of the manure was applied as solid cattle manure from a deep litter stable, while cattle slurry was the main source of manure applied on the fields of Farm A. Van Eekeren et al. (2010) assessed the effect of different fertilizer treatments on soil biota in a grassland experiment on a sandy soil in the Netherlands and found that the total number of earthworms was higher under the farm yard manure (FYM) treatment than the cattle slurry treatments. Although we do not have sufficient information to draw up carbon balances at farm level, we conclude that besides the amount of manure applied, other management characteristics such as stocking management, manure type and consequently soil biota, need to be taken into account. Deriving conclusions on grasslands as potential carbon sinks need specification of their management.

At field level the initial SOM weight concentration varied among fields, especially in the 30–60 cm soil layer (Figure S3). On Farm A, the SOM weight concentration of field 5 was about twice as high as that of the other fields (46 vs. 28 g SOM kg^{-1} soil; 60 vs. 39 Mg ha^{-1}, 30–60 cm soil layer, Figure S3) because of fragmented peat remains. Although all fields were classified as sandy soils, historical data show that peat harvesting took place in the area between the 10th and the 17th century and possibly field 5 was located on a former peatland. However, no detailed historical information is available at field level. On Farm B, the initial SOM weight concentration of the 30–60 cm layer of field 7 was much lower as compared to the other fields (8 vs. 15 g SOM kg^{-1} soil; 37 vs. 69 Mg ha^{-1}, 30–60 cm soil layer, Figure S3). About 35 years ago, field 7 was ploughed to a depth of 60 cm as, at that time, it was thought by farm advisors that this field was too rich in SOM for unknown reasons. This one-time ploughing event led to redistribution of SOM in the soil profile and enhanced decomposition of SOM, which is still reflected in the lower SOM content in the 30–60 cm soil layer of this field as compared to the rest of the farm. It has been suggested in the literature that sequestration rates of SOM decrease with increases in SOM content (e.g. Gulde et al., 2008), but no consistent relationship has been observed on both farms (Figure S3). Furthermore, it is not expected that the fields we sampled, had attained a new equilibrium (steady-state) induced by field management as it takes several decades to reach a steady-state (cf. Macdonald et al., 2015; Fornara et al., 2020).

4.5. Implications

This study underlines that caution should be taken when setting up an SOM monitoring network to comply with environmental directives or for giving out carbon credits. Large variation exists among fields (Fig. 9). Recently, programs on carbon credits have been promoted by the province of Friesland and a few fields per farm will be selected for monitoring (e.g. two fields per farm; National Soil Top Meeting on the 11th of September 2019, Rotterdam, the Netherlands). In Fig. 12 we presented the consequences of deriving conclusions based on the two fields with the highest and lowest changes in SOM stocks over time. As stated before, the sampled soil layer is of utmost important on conclusions. In case we assess the 0–60 cm soil layer, SOM dynamics of Farm A varied between fields from 14.6 Mg ha^{-1} yr^{-1} to −4.0 Mg ha^{-1} yr^{-1}. At Farm B, SOM dynamics varied from 8 to −2.3 Mg ha^{-1} yr^{-1}. A target price of 30 € per Mg CO_2 was set in the province of Friesland (VVM, 2019), which is equivalent to about 0.5 Mg SOM ha^{-1} yr^{-1} (using a factor of two to convert SOC to SOM; Pribyl, 2010). This potentially means that Farm A could be paid an amount of about € 900 ha^{-1} yr^{-1} (14.6 × 2 × 30) or has to pay an amount of € 200 ha^{-1} yr^{-1} (−2.3 × 2 × 30). A similar situation would occur at Farm B.

As the intrinsic variation of the SOM contents in the field is high, SOM trends are associated with a high level of uncertainty, even between fields under equal management. It may therefore be better for policy makers to incentivize agronomical measures that potentially contribute to SOM sequestration, rather than basing payment schemes on highly variable trends. If quantitative underpinning is wished than it is recommended to collect soil samples across the whole farm instead of two fields as trends across fields have shown to be highly variable.

5. Conclusions

The intensive analysis of SOM on two grassland farms to underpin on-farm soil monitoring led us to conclude that a large number of factors is of influence on the calculation of SOM stocks and stock changes and thus possible carbon credits. In this study, we gained quantitative insights into the conversion of SOM weight concentrations to SOM stocks ("How"), effects of agricultural practices on the vertical distribution of SOM (soil depth, "Where"), and "the sampling time and frequency (seasonality "When").. We conclude that:

- Considerable variation exists in pedotransfer curves relating soil bulk density and SOM weight concentration. Therefore, a site specific pedotransfer curve should be used when comparing SOM stocks based on SOM weight concentrations across sites.

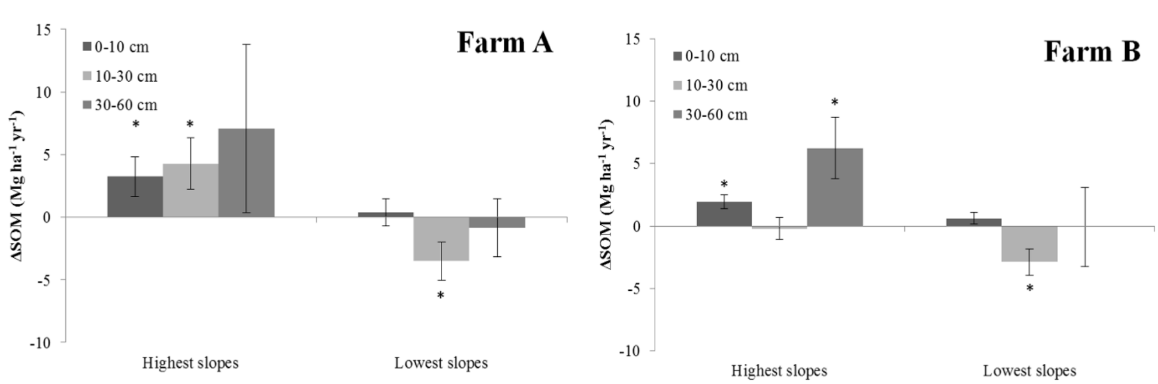

Fig. 12. SOM stock changes over time for Farms A and B per farm and soil layer. The fields with two highest slope values and two lowest slope values were taken. * indicates significance for slope values different from zero at $P < 0.05$.

- Sampling depth of grassland soils should be increased from 10 cm to at least 60 cm for quantification of SOM stocks and stock changes over time.
- Large differences between SOM stock changes over time were found between fields. Yet, few trends were significantly different from zero, indicating that an intensive monitoring period of four years was too short for assessing significant changes of SOM over time. An increase in sampling frequency did not result in finding more significant trends in SOM stocks over time.
- The whole farm should be sampled for quantitative underpinning of carbon payment schemes as trends between fields are highly variable.

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.geoderma.2021.115456.

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