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Soil organic carbon contents of agricultural land in the Netherlands between 1984 and 2004

A. Reijneveld [a], J. van Wensem [b], O. Oenema [c,*]

[a] *Blgg, P.O. Box 115, NL-6860 AC Oosterbeek, The Netherlands*
[b] *Technical Committee on Soil Protection TCB, P.O. Box 30947, NL-2500 GX The Hague, The Netherlands*
[c] *Wageningen University and Research Centre, Alterra, P.O. Box 47, NL-6700 AA Wageningen, The Netherlands*

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ABSTRACT

There is some debate about the likelihood that soil organic carbon (SOC) contents of agricultural land decreases because of global warming and governmental restrictions on animal manure application rates in some countries.

Here, we report on changes in the mean SOC contents of the top soils (0–5 cm) of grassland and the top soil (0–25 cm) of arable land in the Netherlands during the period 1984–2004, using a data base with ~2 million results of SOC determinations from farmers' fields. The analyses were made for all agricultural land on mineral soils and for agricultural land in 9 regions with distinct differences in mean soil textures and SOC contents (marine and riverine clay, peaty clays, reclaimed peat soils, and Aeolian sand and loess), and land uses (arable land and permanent grassland). Except for the regions with peaty clay and reclaimed peat soils, samples with SOC>125 g/kg were designated as peat and peaty soils and excluded from the analyses.

Mean SOC content of soils under arable land in 2003 ranged from 13 to 22 g/kg for sand, loess and clay soils to 59 g/kg for reclaimed peat soils. Mean SOC content of soils under permanent grassland in 2003 ranged from 22 to 56 g/kg for sand and clay soils. The difference in mean SOC contents between grassland and arable land is in part related to the difference in sampling depth.

Mean SOC contents of all mineral soils under grasslands and arable land tended to increase annually by 0.10 and 0.08 g/kg, respectively. We observed large differences in mean trends between regions. Regions with relatively low SOC contents tended to accrue C by up to 0.37 g/kg/year, while regions with relatively high SOC contents (e.g., peaty clays) tended to lose C by up to 0.98 g/kg/year.

In conclusion, mean SOC contents of the top part of mineral soils of agricultural land in most regions in the Netherlands tended to increase slightly during the period 1984–2004. This result contrasts with reports from e.g., United Kingdom and Belgium that suggest decreasing C stocks in arable land possibly due to changes in land use and climate.

1. Introduction

Soils contain vast amounts of organic carbon (C). On a global scale, about 1500 Pg ($1\ \mathrm{Pg} = 10^{15}$ g) is stored in the upper meter of the soil, which is about three times the amount of C in the aboveground biomass and twice the amount of C as CO_2 in the atmosphere (Batjes, 1996; Janzen, 2004). Most of soil C is found in the upper 10 to 20 cm of the soil, and the amount and quality of C in the topsoil is often used as indicator of soil quality and productivity (Allison, 1973; Bauer and Black, 1994; Davidson, 2000). In agriculture, increasing soil organic C (SOC) content is often seen as a desirable objective, especially in organic farming (Mader et al., 2002; Loveland and Webb, 2003; Lal et al., 2004), though the benefits of organic C in soil in terms of fertility arise in part from its decay and not from its accumulation (Janzen; 2004, 2006). Sequestration of C in soils has also been promoted as strategy to mitigate the effects of increasing emissions of greenhouse gases in the atmosphere (Lal et al., 1998; Lal, 2001; Janzen, 2004). Sequestration of C in soils can be increased through a wide range of management measures, including reduced tillage (to decrease mineralization), improved rotations and manure application (Freibauer et al., 2004; Smith et al., 2000, 2005).

Though SOC contents are of considerable interest and in principle can be measured easily, there are few monitoring programs that allow systematic analyzing possible changes in SOC in agricultural land in practice (Janssens et al., 2005; Stolbovoy et al., 2005). Current estimates of changes in SOC at national and continental levels are therefore uncertain (Janssens et al., 2003). So far, most estimates are either derived from long-term field experiments (e.g., Jenkinson and Rayner, 1977; Wadman and De Haan, 1997) and/or simulation modelling (Jenkinson et al., 1987; Jenkinson, 1988; Yang and Janssen, 2000;

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* Corresponding author.
E-mail address: Oene.Oenema@wur.nl (O. Oenema).

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Vleeshouwers and Verhagen, 2002; Freibauer et al., 2004; Vellinga et al., 2004; Smith et al., 2005). Few studies have used repeated inventories for estimating changes in SOC at regional scales (Sleutel et al., 2003; Lettens et al., 2004; Bellamy et al., 2005; Mestdagh et al., 2006).

Some recent studies suggest that SOC of European agricultural land is decreasing (Vleeshouwers and Verhagen, 2002; Sleutel et al., 2003; Bellamy et al., 2005). Such decreases are ascribed to changes in land use, soil cultivation and, possibly, temperature (Davidson and Janssens, 2006). Farmers have concern that decreases in SOC compromises the production capacity of the soil by deterioration of soil physical properties and by impairment of nutrient cycling mechanisms (e.g., Loveland and Webb, 2003). Some arable farmers in the Netherlands are using these arguments to criticize governmental restrictions on the use of animal manure and composts, although these restrictions are meant to regulate the inputs of nutrients and heavy metals. Additions of animal manure and composts are often perceived as inherently desirable.

Agricultural soils in the Netherlands receive relatively large inputs of animal manure, because of the high livestock density (Oenema and Berentsen, 2004). The mean input of effective C, i.e., the C that remains after one year of decomposition (Yang and Janssen, 2000) via animal manure to agricultural land in the Netherlands in the 1990s has been estimated at ~40% of the total input of effective C (Velthof, 2005). Most effective C was derived from crop residues (~60%). Less than 2% was derived from composts. Total input of C via animal manure has slightly decreased during the last decade, because of the decreasing livestock density (mainly through a decrease in dairy cow number).

In this paper, we explore the potentials of a data base with ~2 million results of soil analyses from farmers' fields, for assessing changes in SOC of arable land and grassland in the Netherlands during the period 1984–2004. All soil samples have been taken and analyzed by one laboratory, on request of farmers to assess the soil fertility level (SOC, pH, plant nutrients) of specific fields. We distinguished the land use types: arable land, grassland and maize land (used for making silage maize to feed cattle). All data for these types of land use and for nine specific regions were analyzed for changes in SOC over time and for differences between regions. The analyses were also used to verify whether farmers' concerns about decreasing SOC levels following implementation of governmental restrictions on the use of manure and compost, could be confirmed by data from farmers' fields.

2. Materials and methods

2.1. Site description

The Netherlands (NL) is situated along the North Sea in the western deltas of the rivers Rhine, Meuse and Scheldt and the Northern delta of the Ems (Fig. 1). Its surface area is 34,000 km^2, with 470 inhabitants per km^2. The northern and western parts of the Netherlands have marine clay, peaty clay and peat soils, with shallow groundwater levels (0.2–1.0 m below surface level). The southern and eastern parts have glacial and Aeolian sands and Aeolian loess, with shallow to relatively deep groundwater level (1–10 m below surface level). Riverine clay soils dominate along the rivers in the central part. About 60% of the total surface area is agricultural land (20,000 km^2), 15% surface waters, 15% urban and infra-structural area and 10% natural area (forests, heath land, wetlands). Approximately 50% of the agricultural land is intensively managed permanent grasslands, 35% arable land (potatoes, sugar beet, cereals, bulb flowers), 10% maize land (for silage maize), and 5% is horticultural land. The area of agricultural land has declined by on average almost 100 km^2 per year (10,000 ha per year) during the last 50 years (Fig. 2). Silage maize was introduced in the late 1960s, at the expense of arable land (for instance rye disappeared) and permanent grassland.

Nine areas were selected for analyzing trends in SOC at regional level (Fig. 1). Areas were chosen on the basis of their relative homogeneity in soil type and land use, and identified by the zip code of the farmers' address. Land use on marine clay soils is dominated by arable land, though some areas are used for grassland-based dairy farming as well. Peaty clays are used for dairy farming and thus mainly covered by permanent grasslands, while reclaimed peat soils are mainly used as arable land. Land use on sand and loess in the south is a mixture of permanent grassland, maize land and arable land. A brief characterization of the soils per region is given in Table 1.

2.2. Data collection and representativeness

All samples were taken and analyzed by the laboratory for soil and crop analyses Blgg (www.blgg.nl), founded in 1928 as private branch off of the former Institute of Soil Fertility Research in Haren (Harmsen, 1991). Soil samples were analyzed at farmers' request and results documented in reports to farmers only. Summaries (means, median, maximum and minimum values) were incidentally made in the past (e.g., Kortleven, 1962; Hoogerkamp, 1973). From 1984, results were compiled and archived anonymously in an electronic data base. Until 1952, Blgg was the only laboratory that analyzed soil samples for farmers. Nowadays, Blgg analyses about 80% of the soil samples offered to the market. Between 1975 and 1995, the number of soil samples was about 150,000 per year. Between 1995 and 2005, the number of samples analyzed by Blgg decreased by about 50%, mainly because farmers became less interested in soil analyses (soil fertility is already high, up-scaling decreased number of farms and fields, manure policy focused on nutrient inputs and outputs and not on soil fertility level), and because of competition by other labs. Nowadays, about 20% of the farmers have their land analyzed every four years. Hence, the number of samples decreased over time, and also varied between years.

Fields were sampled by taking 40 samples when walking in a 'W'-like pattern over the fields (maximum area 2 ha), and these samples were bulked and mixed to one sample for subsequent analysis. Two or more samples were taken for fields larger than 2 ha, depending on the area. Standard sampling depth for permanent grassland was 0–5 cm until 2000 and 0–10 cm thereafter. Standard sampling depth for arable, maize, and horticultural lands is 0–25 cm. Because of the change in standard sampling depth in 2000, we analyzed only data from the period 1984 to 2000 for grassland. For arable land and maize land, we analyzed data from the period 1984–2004.

All samples have been analyzed following standard procedures. In clay and sand soils, SOC was determined by wet oxidation (until 1994), and elemental C analysis following dry combustion. Reference samples were always included, to check the analytical precision throughout the year(s). In organic-rich soil (peat soils) with SOC > 125 g/kg, SOC was determined by loss on ignition (NEN 5754, 2005), using corrections for inorganic carbonates, and percentage clay in the soil. Loss on ignition (LOI) was converted to SOC by $\mathrm{SOC} = 0.5 \times \mathrm{LOI}$. There is considerable uncertainty in a conversion factor of LOI to SOC (see Rosell et al. (2001) for a discussion), which may have affected the quality of the SOC data of peat soils in our study. The overall error of SOC determination (sampling and analyses errors) is estimated at ± 5 g/kg for SOC contents < 50 g/kg and at ± 10% of the SOC content for SOC contents > 50 g/kg.

2.3. Data processing and statistical analysis

The way in which the soil samples have been taken affects the way the results have to be analyzed as well as the statistical inference (De Gruijter et al., 2006). Our interest is 'changes over time in mean SOC contents within well-defined regions and for specific land uses'. We assumed that the selected data from the data base can be analyzed as if it was a random sample, and that the errors in the estimates remain small enough to prevent grossly misleading conclusions.

Results of SOC analyses per land use type and/or per region and year were averaged and distributions were analyzed for means, medians, skewness and kurtosis, using Genstat (GenStat, 2003) and Microsoft Excel. As we were mainly interested in changes over time (and not so

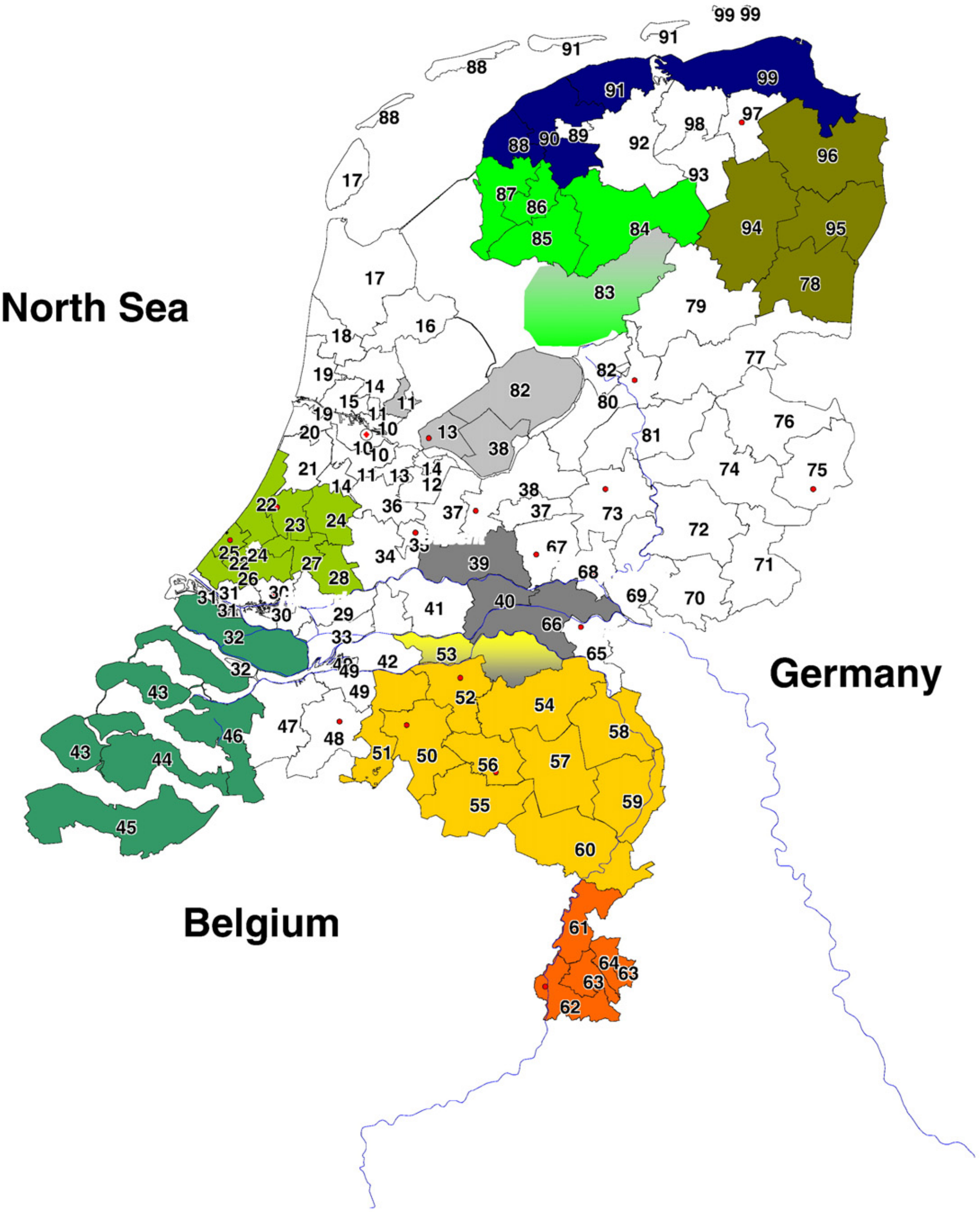

Fig. 1. The Netherlands with the locations of the 9 selected regions. Numbers refer to zip-codes (see Table 1).

much in differences between regions or in differences between two specific periods), we used simple regression analyses to detect trends in means and medians over years. We corrected for autocorrelation, by using the following statistical model $y_t = a_0 + b_1 x + b_2 y_{t-1} + b_3 y_{t-4} + \varepsilon_t$, where y_t is the mean SOC content in year t, a_0 is a constant, x is the year number, y_{t-1} is the mean SOC content in year $t-1$, y_{t-4} is the mean SOC content in year $t-4$, b_1, b_2, and b_3 are coefficients, and ε_t is the error term (De Gruijter et al., 2006). We checked for homogeneity of variance of the mean SOC content between years using Genstat (GenStat, 2003). We also checked for the effects of variations and mean decreases in the number of samples between years on the statistical significance of the changes in SOC over time (using Genstat) and found that these effects were negligibly small (because of the large number of samples and the relatively small variations). The average number of samples analyzed per region, land use and year was 1850 (range 100–7500), with larger numbers for large regions.

3. Results

3.1. Mean soil characteristics of the 9 regions in 2003

Table 1 provides an overview of the areas and mean soil characteristics for the dominant land uses of the 9 regions in 2003. Some regions had rather similar soil characteristics (regions 2 and 3), but in general there were distinct differences between regions in mean clay and C contents and in soil pH. The areas of the 9 regions ranged from ~ 14,000 to 153,000 ha (Table 1).

Mean SOC contents of arable land (0–25 cm) in 2003 ranged from 13 to 17 g/kg for marine clay and loess soils to 59 for reclaimed peat soil (sandy soils). Soils in grassland (0–10 cm) had much higher SOC contents than soils used for arable land. Mean SOC content of permanent grassland on marine and riverine clay soils in 2003 was 48 and 56 g/kg, respectively (Table 1). The two areas with peaty clays

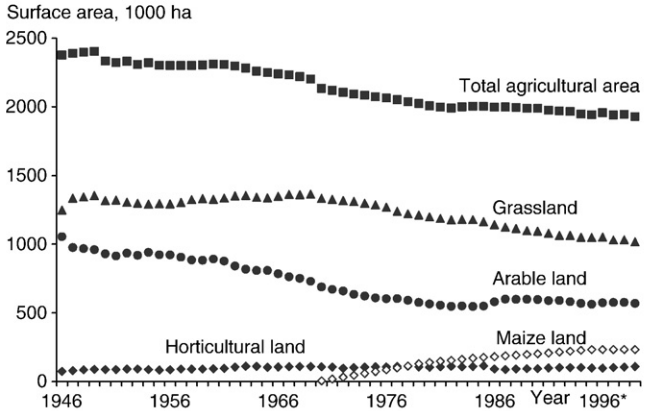

Fig. 2. Changes in the areas of grassland, arable land, horticultural land and maize land between 1950 and 2000.

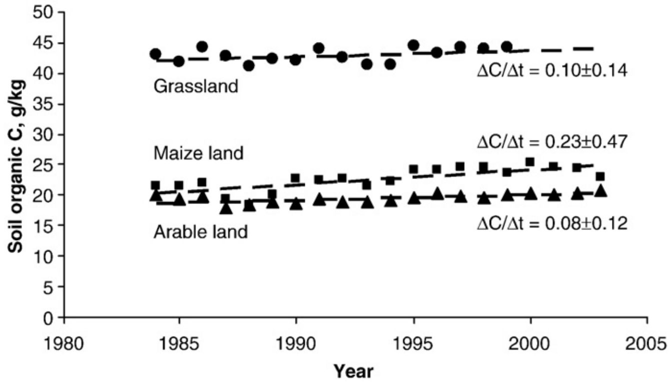

Fig. 3. Changes in mean soil organic carbon contents of grassland (period 1984–2000), maize land (1984–2004) and arable land (1984–2004) in the Netherlands. The mean annual change in SOC is indicated as $\Delta C/\Delta t$, in g/kg/yr.

(regions 4 and 5) had much higher SOC contents than the mineral soils. The peaty clays in the west of the Netherlands had a mean SOC of 85 g/kg and those in the north 133 g/kg. The relatively low SOC content of the top soil in peaty clays in the western part of the Netherlands reflects the amendment of the topsoil with sewage and urban wastes, with a lower C content than peat, in the 17th–20th centuries.

Coefficients of variation of mean SOC contents per regions ranged from 20 to 50% (Table 1). These values compare well with values reported by Sleutel et al. (2003) for Belgium, and reflect heterogeneity in soil types and soil wetness conditions within regions.

3.2. Changes in SOC content of grassland and arable land in the Netherlands

Mean SOC contents of mineral soils (clay and sand soils combined) under grassland (soil layer 0–5 cm), arable land and maize land (upper 25 cm) in the Netherlands tended to increase with 0.10, 0.08 and 0.23 g C per kg soil per year during the period 1984–2000, 1984–2004 and 1984–2004, respectively (Fig. 3). Variations in annual means were small. Note that samples containing >125 g/kg (i.e. peat samples) had been removed from these sample populations.

The apparent increase in the SOC content of maize land is in part related to the increasing area of maize land (Fig. 2). The area of silage maize has expanded rapidly from the 1960s onwards, starting in the southern half on sandy soils, but from the 1980s onwards silage maize has been grown on sandy and clay soils throughout the country at the expense of permanent grassland and arable land. Because of the increasing area of maize land (Fig. 2), we excluded maize land from further examination.

Table 1
Characteristics of the nine studied regions.

Regions	Zip codes	Dominant land use	Area (ha)	Clay (%)	pH	SOC (g/kg)
1. Marine clay, north	88, 90, 91, 99	Grassland	40,544	29 ± 9	6.3 ± 0.8	48 ± 21
2. Marine clay, south-west	32, 43–46	Arable land	70,914	20 ± 7	7.4 ± 0.3	13 ± 6
3. Marine clay, west-central	11, 13, 38, 82, 83	Arable land	125,936	22 ± 10	7.4 ± 0.2	17 ± 9
4. Riverine clay, central	39, 40,53, 66	Grassland	46,723	35 ± 12	5.6 ± 0.7	56 ± 26
5. Peaty clay, north	83–87	Grassland	152,620	27 ± 10	4.9 ± 0.4	133 ± 52
6. Peaty clay, west	22–28	Grassland	37,466	19 ± 7	5.6 ± 0.8	85 ± 20
7. Reclaimed peat, north-east	78, 94–96	Arable land	62,593	<8	4.9 ± 0.3	59 ± 29
8. Sand, south	50–60	Grassland	82,391	<8	5.4 ± 0,5	22 ± 8
9. Loess, south	61–64	Arable land	13,909	14 ± 2	6.6 ± 0.6	14 ± 4

Means and standard deviations for clay content (particles <2 μm), soil pH (determined in 1 M KCl) and soil organic carbon (SOC) content for the year 2003. The samples analyzed per region ranged from 160 in region 9 to 1405 in region 1 in 2003. The zip codes refer to regions shown in Fig. 1.

Frequency distributions of SOC contents of all mineral soils (sand and clay soils combined) under grassland in the Netherlands were bimodal and skewed (Fig. 4). The bimodal character of the frequency distribution of SOC contents reflects the presence of regions with distinct differences in mean SOC contents (see Table 1). Because of the skewed frequency distribution, annual median SOC contents were 6 to 8 g/kg lower than annual mean SOC contents. Over time, skewness tended to decrease, i.e., the percentage samples with relatively low SOC (<25 g/kg) tended to decrease and thus the percentage samples with SOC contents in the range of especially 30–75 g/kg tended to increase. This suggests that soils with low C contents accrued SOC; the number of samples with low SOC contents decreased relative to the number of samples from soils with high SOC contents.

3.3. Changes in SOC contents of grassland and arable land in 9 regions

Regional differences in annual mean changes in SOC were relatively large (Table 2). The mineral soils tended to accrue C, while peaty soils tended to lose C. Annual mean changes in SOC ranged from −0.98 ± 0.81 g/kg for region 5 with peaty clays to +0.37 ± 0.17 g/kg for region 4 with riverine clay soils. Decreases in SOC occurred on soils with relatively high SOC contents (peaty clays), and increases in SOC on soils with relatively low SOC. Increases and decreases in mean SOC occurred both on grassland and arable land.

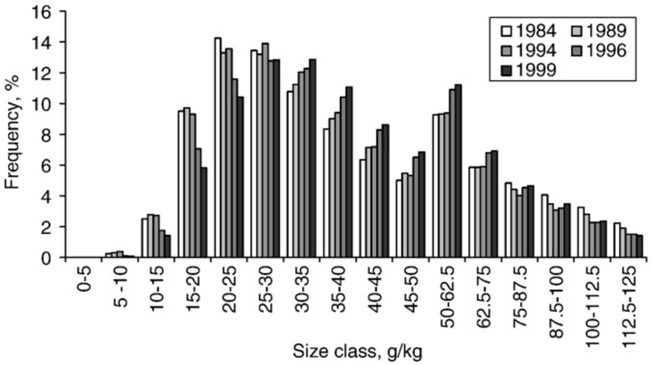

Fig. 4. Frequency distributions of SOC classes for grasslands on mineral soils in the Netherlands analyzed in 1984, 1989, 1994, 1996, 1998 and 1999. Note that samples with more than 125 g/kg of C were removed (>4 times medium value).

Table 2
Overall mean SOC contents (in g/kg), linear regression coefficients (slope b with standard error (se), in g/kg/yr) and Spearman correlation coefficients (R^2), for grassland and arable land of selected regions and the Netherlands.

Regions	Land use	Summary statistics			
		Mean	Slope b (±se)	R^2	# of samples
1. Marine clay, north	Grassland	57	−0.55 (0.16)	0.46	16,849
	Arable land	13	−0.02 (0.04)	0.01	23,830
2. Marine clay, south-west	Arable land	12	0.03 (0.02)	0.13	56,418
3. Marine clay, central-west	Arable land	21	0.18 (0.12)	0.11	4615
4. Riverine clay, central	Grassland	53	0.37 (0.17)	0.25	12,660
5. Peaty clay, north	Grassland	155	−0.98 (0.81)	0.09	9806
6. Peaty clay, west	Grassland	88	−0.27 (0.28)	0.06	5889
7. Reclaimed peat, north-east	Grassland	70	−0.07 (0.36)	0.00	4583
	Arable land	63	0.08 (0.10)	0.04	40,497
8. Sand, south	Grassland	24	0.18 (0.05)	0.47	57,594
	Arable land	17	0.01 (0.02)	0.02	49,344
9. Loess, south	Grassland	33	0.34 (0.11)	0.39	7720
	Arable land	13	0.02 (0.01)	0.10	13,977
Netherlands,	Grassland	43	0.10 (0.06)	0.16	589,899
	Arable land	20	0.08 (0.02)	0.39	673,770
	Maize land	23	0.23 (0.05)	0.58	112,168

The regression coefficient indicates the mean change of the mean SOC per year. Last column shows number of samples per regions for the period 1984–2004 for arable land and 1984–2000 for grassland.

Table 3
Descriptive statistics of the mean SOC contents for regions in 1984/85 and in 1999/2000.

Regions	1984/85				1999/2000			
	Samples #	Mean g/kg	St dev g/kg	Kurtosis g/kg	Samples #	Mean g/kg	St dev g/kg	Kurtosis g/kg
1. Grassland	300	62	3.1	−0.3	534	54	2.6	1.7
2. Arable land	3277	13	0.5	23.1	1541	12	0.5	9.2
3. Arable land	682	20	0.6	−0.0	165	23	0.5	0.2
4. Grassland	723	54	2.6	0.1	383	57	2.1	0.4
5. Grassland	261	156	8.0	−0.9	449	144	5.9	0.2
6. Grassland	322	89	2.5	0.5	100	94	2.9	−0.2
7. Arable land	2517	63	3.3	12.4	1517	64	3.3	12.3
8. Grassland	4293	24	1.0	39.0	1130	26	1.2	67.9
9. Arable land	785	14	0.4	11.6	615	14	0.6	40.8
Grassland	40378	43	2.6	0.7	28260	44	2.3	1.1
Arable land	24716	20	1.5	12.7	32618	20	1.4	10.4

Frequency distributions of SOC in grassland soils of region 1 are shown in Fig. 5. Here, the percentage samples with 20–40 and 40–60 g C per kg increased over time and those with more than 60 g C per kg decreased over time. This pattern is consistent with a decreasing SOC content over time (Table 2). Distributions were broad (low kurtosis) and slightly skewed.

On average, frequency distributions of SOC were more peaked (higher kurtosis) on arable land than on grassland (Table 3). A high kurtosis reflects a narrow distribution and a more homogeneous population of soil samples. Clearly, arable land is found on well-drained and rather homogenous soils, while grassland is situated on both well-drained and poorly drained soils and all soil types. The frequency distribution of SOC contents of arable land in region 2 is shown in Fig. 6. About 80% of the samples have SOC contents in the narrow range of 5 to 15 g/kg, while only 20% is in the range of 15 to 50 g/kg. There were no significant trends in SOC content and in distribution patterns in region 2 (Table 2, Fig. 6). The sandy soils in the south (region 8) are also homogenous and the frequency distributions of the SOC have a high kurtosis. Region 8 is in the centre of the high-density livestock area, and the application of large amounts of animal manure in the second half of the 20th century may have contributed to the increasing SOC contents in these soils (Table 2). The loess soils of region 9 are also homogeneous (high kurtosis). Region 9 is located near the high-density livestock area, and SOC contents tend to increase over time, in soils under grassland and arable land (Table 2).

4. Discussion

4.1. General trends in SOC contents

Organic C contents in mineral soils under grassland and arable land in the Netherlands tended to increase annually by on average 0.10 and 0.08 g/kg, respectively, during the last two decades. This increase occurred for the dominant land use types (Fig. 1), but with large regional differences (Table 2). This result contrasts with reports from United Kingdom (Bellamy et al., 2005) and Belgium (Sleutel et al., 2003), which indicate decreasing SOC contents in agricultural soils by 0–1% per year (relative). Our results are also in contrast with farmers' concern that SOC contents are decreasing because of increasing restrictions on manure and compost applications. Governmental restrictions on the use of animal manure have been tightened from 1984 onwards (Oenema and Berentsen, 2004; Schroder and Neeteson, 2008), and have contributed to a slight decrease over time in organic C input to agricultural soils (Velthof, 2005). However, these restrictions are not reflected in decreasing SOC contents of mineral soils under grasslands and arable land.

Kortleven (1963) summarized results of soil organic matter (SOM) analyses of grassland (0–5 cm) from the same laboratory (Blgg) in the late 1950s, and arrived at a mean of 10.1% for sand and clay soils. They used the so-called Van Bemmelen factor of 1.724 to estimate SOM from SOC data, suggesting that the mean SOC content was 58 g/kg.

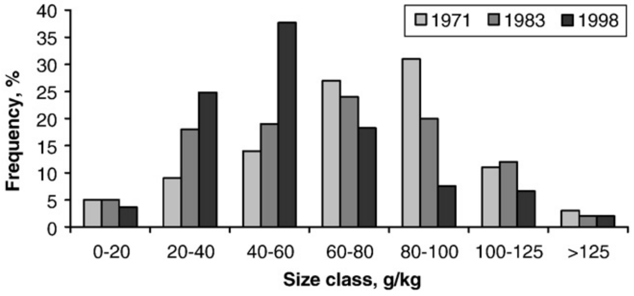

Fig. 5. Frequency distributions of SOC classes for grasslands on marine clay soils in region 1 in 1971, 1980, 1983 and 1998. Information about samples from 1971 to 1980 were obtained from written records at Blgg.

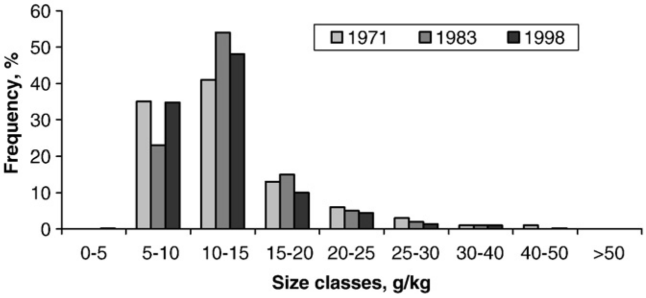

Fig. 6. Frequency distributions of SOC classes for arable land on marine clay soils in region 2 in 1971, 1980, 1983 and 1998. Information about samples from 1971 to 1980 were obtained from written records at Blgg.

This value is very close to the overall mean SOC content of 60 g/kg for grassland soils in the period 1984–2000, suggesting that SOC contents of grasslands have been stable or slightly increasing during the last 50 years.

Kortleven (1963) estimated a mean SOC content of 18 g/kg for arable land on sand and clay soils in the 1950s. This estimate is lower than the overall mean of 25.7 g/kg and 19.5 g/kg for arable land under mineral soils without and with corrections of samples with SOC contents >125 g/g, respectively. His estimate is lower than ours, but Kortleven (1963) did not include region 7 in his estimate. This comparison suggests that SOC contents of arable land on mineral clay and sand soils have remained stable or have slightly increased during the last 50 years.

4.2. Regional differences in changes of SOC contents

Mean SOC contents of mineral soils under arable land in regions 2, 3, 8 and 9 compare reasonably well with the mean SOC content of 10 to 20 g/kg in cropland of nearby countries Belgium (Sleutel et al., 2003), France (Arrouays et al., 2002), England (Bellamy et al., 2005), and other countries in western Europe (Batjes, 1996), despite differences in cropping systems, manure and fertilizer applications and climate. Interestingly, the SOC contents in regions 2, 3, 8 and 9 tended to increase, which is unlike the observed changes in Belgium and England. Changes over time in the SOC of grassland were related to the period-average SOC content; the higher the average SOC content, the larger the decrease in SOC content (Fig. 7). The latter observation has been noted also by Bellamy et al. (2005), Sleutel et al. (2003) and Lark et al. (2006). It may reflect the effects of drainage, land use changes and possibly climate change.

The mean SOC content of reclaimed peat soils of region 7 was a factor 2 to 3 higher than those in regions 2, 3, 8 and 9 (Table 1). Our data suggest that the SOC content of the reclaimed soils under arable land have on average slightly increased during the last two decades. This may reflect the use of relatively large amounts of animal manure in this region. It also suggests that the remaining peat residues in the soil have a relatively high resistance to decay.

Grassland soils showed both decreasing trends (regions 1, 5, 6 and 7) and increasing trends (regions 4, 8 and 9) in SOC content (Fig. 7). The decrease observed in peaty clay soils with a relatively high SOC content (regions 5, 6 and 7) is likely related to the increased decomposition of SOC (peat) following improved drainage from the first half of the 20th century onwards (Vellinga and André, 1999). Decreasing SOC contents in clay soils in region 1 (Fig. 5) are more puzzling. Region 1 is situated near the coast of the Wadden Sea and the land use in this area may switch from grassland to arable land (to grow potatoes and bulb flowers) and vice versa, depending in part on market conditions. Exchange of land between arable farms and grassland-based dairy farms has increase during the last decades. Decreasing SOC content in grassland soils in Belgium was also related to changes in land use (Mestdagh et al., 2004, 2006).

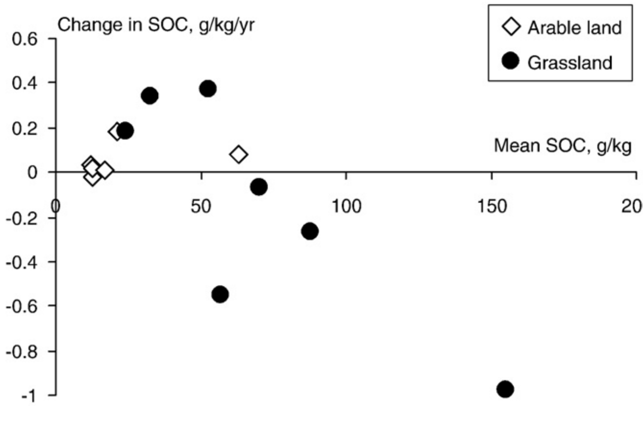

Fig. 7. Relationship between mean SOC content and mean changes in SOC contents for grassland during 1984–2000 and for arable land during 1984–2004, as observed in the nine regions sampled.

Slightly increasing SOC contents of grassland soils were found in regions 4, 8 and 9. Increasing SOC contents suggest that C losses through decay are smaller than C inputs via crop residues and animal manure during the last decades. Inputs of effective organic matter via crop residues and animal manure have been rather stable or were slightly decreasing in the period 1995–2002 (Velthof, 2005). Increasing SOC in grassland soils may also reflect that these soils were previously used as arable land and that they were sown to grassland. Commonly, soils under well-established permanent grassland have much higher SOC content than similar soils under arable land (Hoogerkamp, 1973; Jenkinson, 1988). The SOC content of grassland also depends on the management; grazed pastures have higher SOC content than mown-only grasslands (Hassink and Neeteson, 1991).

4.3. Effects of grassland renovation

Most grassland in the Netherlands is ‘permanent’ grassland, with *Lolium perenne* L as dominant grass species, and is intensively managed with 5 to 7 harvests per annum and with a cumulative herbage production of 8000 to 14,000 kg dry matter per ha per year. However, grassland management has undergone various changes in the 20th century (Bieleman, 2000; Vellinga et al., 2004), which will have influenced the balance of SOC decay and accrual. Major changes include drainage of wet soils, fertilization, soil amelioration and grassland reseeding. Annually, 5 to 10% of the total grassland area is ploughed down and reseeded with higher yielding grass species, with or without growing potatoes or bulbs for one season between ploughing and reseeding (Hoogerkamp, 1973). Vellinga et al. (2004) estimated that the increased decay of organic matter due to grassland renovation has emitted 0.4 to 1.1 Mton CO_2 into the atmosphere annually, between 1970 and 2000. This translates to an average 3000 to 9000 kg C per ha or to a SOC loss of 3 to 9 g/kg in the top 10 cm of grassland soils, over this 30-year period. Our data do not reflect decreases in mean SOC content of grasslands of this order (Fig. 3). Further, grassland renovation has remained at a steady level of 5 to 10% of the grassland area for at least 50 years (Hoogerkamp, 1973). Hofstee (1985) noted large changes in the area of grassland relative to arable land for the northern area of the Netherlands for the period 1750–1930, but there are no systematic inventories for the whole country for this period.

4.4. Uncertainties

Despite the large number of samples used in this study (nearly 2 million SOC analyses in the period 1984–2004), there is considerable uncertainty in the estimated changes over time. The uncertainty arises from the facts that (i) mean changes in SOC content are small, (ii) selected regions did have inherent soil variability and soil samples were not taken from fixed positions, fields and farms over time, (iii) land use in practice is dynamic, (iv) the number of samples changed over time. We address these uncertainties below.

The mean annual changes in SOC content over time ranged from −0.98 to +0.37 g/kg, which is much less than the accuracy of SOC measurement of individual samples (±5 g/kg for sampling and determination). Hence, a large number of samples are needed to be able to detect significant changes. The standard errors of the linear regression coefficients were proportionally to the mean SOC content and were 1–4 times smaller than the regression coefficients (Table 2). Extending the number of years will contribute to lowering the uncertainty in trend. Saby et al. (2008) concluded that a time interval of about 10 years is required to detect significant changes in SOC content of soil monitoring sites that are sampled repeatedly.

Soils are variable in space, even within well-defined landscape or soil units. In this study, regions were defined on the basis of overlays of

1:50,000 soil maps (Van der Pouw and Finke, 1999; Visschers et al., 2007) and Zip code maps, taking into account that the minimum number of analyses per year within a region is >100. The sampling locations within these regions have been selected on the basis of requests by farmers. The inherent assumption in our study is that the estimated SOC content, averaged over the samples taken within a region in a year, is approximately equal to the true mean SOC content. We deleted SOC samples containing >125 g/kg in the sample populations from mineral soils, as the number of these organic-rich samples varied from year to year (from 0 to 10%), decreased over time, and as they had a relatively large effect on the sample mean. The area of peat soils in the Netherlands has greatly diminished over the last centuries due to peat digging as well as increased mineralization following drainage and soil cultivation (De Vries et al., 2008). Hence, peat soils lose SOC, and the decreasing SOC content of the peaty clays in regions 5 and 6 confirm this.

Land use change has a huge effect on SOC contents (e.g., Jenkinson, 1988; Smith et al., 2000; Guo and Gifford, 2002; Smith et al., 2005; Freibauer et al., 2004; Vellinga et al., 2004). After a change in land use from permanent grassland to arable land and vice versa, it may take decades or an even a century before a new equilibrium level is established (Kortleven, 1963; Hoogerkamp, 1973; Jenkinson, 1988). The current land use of the sampling locations is known, but the history of the sampling locations is not always known. The locations may have been in use as grassland or arable land for decades, but may also have been in use for only a few years. Hence, the grassland sample populations include also relatively young grassland and recently resown grasslands. Similarly, the arable land sample populations likely include 'old' and 'young' arable lands. Though the total areas of grassland and arable land depict rather similar and stable trends over time (Fig. 2), this does not say much about the dynamics in land use changes. If the exchange of land used for grassland and arable cropping would have increased in frequency with time, then it will tend to globally lower the high mean SOC values of grasslands and to increase the low mean SOC values of arable lands. The sales of grass seed have remained fairly constant during the last few decades, but the conversion of permanent grassland for leys and the areas of leys ploughed up in rotation have slightly increased (Vellinga et al., 2004). Such changes may indeed contribute to a lowering of the mean SOC of grassland and to increasing the mean SOC of arable land. Evidently, the unknown history induces uncertainty in explaining the cause of the observed changes in SOC contents in our data, as well as in many other data.

The fourth factor contributing to possible uncertainty in the observed changes in SOC is the decreasing number of samples over time. Because of the already-high-soil-fertility-status of many agricultural soils, the change to larger fields and farms, and because of the manure policy, various farmers tend to minimize on soil analyses. However, correcting for the decreasing number of samples over time changed the regression coefficients and standard deviations only marginally. Further, it is possible that the decrease in number of samples over time is larger for heavily manured fields than for fields that received the recommended dose, and this variable decrease in the number of samples may contribute to a biased sample population. This possibility should be explored further, for example by re-sampling the data base which may avoid biases relative to different sampling resolutions in time (e.g., Saby et al., 2008; Lemercier et al., 2008).

5. Conclusions

The data base explored in this study contains vast amounts of soil fertility characteristics of the top soil of agricultural land in the Netherlands from 1930 onward. We have only explored the digitally available SOC data for the period 1984–2004 (~2 million data). Our data suggests that SOC contents of mineral soils under both grassland and arable land are slightly increasing, though there are large regional differences. This result contrasts with recent reports (Bellamy et al., 2005; Sleutel et al., 2003; Vleeshouwers and Verhagen, 2002) about SOC depletion in agricultural land in Europe. It also contrasts with farmers' concerns about decreasing SOC, following the implementation of the manure policy which restricts the use of animal manure and composts. Further, the estimated decreases in SOC of peat soils confirm recent soil mapping observations that these soils are vanishing in the Netherlands (De Vries et al., 2008).

The data base allows making regional analyses of changes in SOC content. We made a selection of 9 regions, on the basis of dominant soil types and land uses. Between regions, mean SOC contents of soils under grassland varied by a factor of 3 and those under arable land by a factor of 5, and although the standard deviations of the mean SOC were relatively large (Table 1), the division in regions was helpful in differentiating SOC changes (Table 2).

Evidently, the huge number of analyses data collected in a uniform way over an extended period is a major advantage of the data base analyzed in this study. Until 2004, the sampling locations were not geo-referenced; the sample locations are chosen on farmers' requests and are only known by the field name and the farmers' address. Also, the uncertainty about previous land use of the sampling locations is a limitation of the current data base. In principle, the data base covers soil data from 1928 till present. Evidently, the current data base can also be used as check and extension of the Netherlands soil sampling program, which covers 'only' 2524 sampling points, selected by stratified random sampling (Visschers et al., 2007).

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References

Allison, F.E., 1973. Soil Organic Matter and its Role in Crop Production. Elsevier, New York.

Arrouays, D., Balesdent, J., Germon, J.C., Jayet, P.A., Soussana, J.F., Stengel, P., 2002. Contribution à la lutte contre l'effet de serre. Stocker du carbone dans les sols agricoles de France?. Expertise scientifique collective INRA 332 pp.

Batjes, N.H., 1996. Total carbon and nitrogen in soil of the world. European Journal of Soil Science 47, 151—163.

Bauer, A., Black, A.L., 1994. Quantification of the effect of soil organic matter content on soil productivity. Soil Science Society of America Journal 58, 185—193.

Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M., Kirk, G.J.D., 2005. Carbon losses from all soils across England and Wales 1978–2003. Nature 937, 245—248.

Bieleman, J., 2000. Agriculture (in Dutch). Techniek in Nederland in de Twintigste Eeuw III Landbouw Voeding. Walburg Press, Zutphen, pp. 11—233.

Davidson, D.A., 2000. Soil quality assessment: recent advances and controversies. Progress in Environmental Sciences 2, 342—350.

Davidson, E.A., Janssens, I.A., 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature 440, 165—173.

De Gruijter, J.J., Brus, D.J., Bierkens, M.F.P., Knotters, M., 2006. Sampling for Natural Resource Monitoring. Springer, Berlin. 332. pp.

De Vries, F., Kuikman, P.J., Hendriks, C.M.A., 2008. Vanishing peat soils in the Netherlands (in Dutch). Bodem 1, 14—17.

Freibauer, A., Rounsevell, M.P.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in European agricultural soils. Geoderma 122, 1—23.

GenStat, 2003. GenStat for Windows. Release 7.1. Seventh Edition. VSN International Ltd., Oxford.

Guo, L.B., Gifford, R.M., 2002. Soil carbon stocks and land use change: a meta analysis. Global Change Biology 8, 345—360.

Harmsen, K., 1991. The Institute for Soil Fertility Research 1890–1990. Netherlands Journal of Agricultural Science 39, 205—220.

Hassink, J., Neeteson, J.J., 1991. Effect of grassland management on the amounts of soil organic N and C. Netherlands Journal of Agricultural Science 39, 225—236.

Hofstee, E.W., 1985. Groningen from Grassland to Arable Land 1750–1930. Pudoc, Wageningen. 422 pp.

Hoogerkamp, M., 1973. Accumulation of Organic Matter Under Grassland and Its Effects on Yields of Grassland and Arable Crops (in Dutch). Pudoc, Wageningen. Agricultural Research Report 806 235 pp.

Janssens, I.A., Freibauer, A., Ciais, P., Smith, P., Nabuurs, G.J., Folberth, G., Schlamadinger, B., Hutjes, R.W.A., Ceulemans, R., Schulze, E.D., Valentini, R., Dolman, A.J., 2003. Europe's terrestrial biosphere absorbs 7 to 12% of European anthropogenic CO_2 emissions. Science 300, 1538—1542.

Janssens, I.A., Freibauer, A., Schlamadinger, B., 2005. The carbon budget of terrestrial ecosystems at country scale. A European case study. Biogeosciences 2, 15—27.

Janzen, H.H., 2004. Carbon cycling in earth systems—a soil science perspective. Agriculture, Ecosystems & Environment 104, 399—417.

Janzen, H.H., 2006. The soil carbon dilemma: shall we hoard it or use it? Soil Biology & Biochemistry 38, 419—424.

Jenkinson, D.S., 1988. Soil organic matter and its dynamics, In: Wild, A. (Ed.), Soil Conditions and Plant Growth, 11th edition. Longman, New York, pp. 564—607.

Jenkinson, D.S., Rayner, J.H., 1977. The turnover of soil organic matter in some of the Rothamsted classical experiments. Soil Science 123, 298—305.

Jenkinson, D.S., Hart, P.B.S., Rayner, J.H., Parry, L.C., 1987. Modelling the turnover of organic matter in long-term experiments at Rothamsted. In: Colley, J.H. (ed.) Soil organic matter dynamics and soil productivity. INTECOL Bulletin, 1987, 15.

Kortleven, J., 1963. Quantitative aspects of the build up and decay of soil organic matter (in Dutch). Verslagen Landbouwkundige Onderzoekingen 69, 1, 109 pp.

Lal, R., 2001. World cropland soils as a source or sink for atmospheric carbon. Advances in Agronomy 71, 145—191.

Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), 1998. Soil Processes and the Carbon Cycle. CRC Press, Boca Raton, Boston. 609 pp.

Lal, R., Griffin, M., Apt, J., Grave, L., Morgan, M.G., 2004. Managing soil carbon. Science 304, 393.

Lark, R.M., Bellamy, P.H., Kirk, G.J.D., 2006. Baseline values and change in the soil, and implications for monitoring. European Journal of Soil Science 57, 916—921.

Lemercier, B., Gaudin, L., Walter, C., Aurousseau, P., Arrouays, D., Schvartz, C., Saby, N.P.A., Follain, S., Abrassart, J., 2008. Soil phosphorus monitoring at the regional level by means of a soil test database. Soil Use and Management 24, 131—138 June.

Lettens, S., Van Orshoven, J., Van Wesemael, B., Muys, B., 2004. Soil organic and inorganic carbon contents of landscape units in Belgium derived using data from 1950 to 1970. Soil Use and Management 20, 40—70.

Loveland, P., Webb, J., 2003. Is there a critical level of organic matter in the agricultural soils of temperate regions: a review. Soil & Tillage Research 70, 1—18.

Mader, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. Science 296, 1694—1697.

Mestdagh, I., Lootens, P., Van Cleemput, O., Carlier, L., 2004. Soil organic carbon stocks in Flemish grassland soils: how accurate are they? Grass and Forage Science 59, 310—317.

Mestdagh, I., Lootens, P., Van Cleemput, O., Carlier, L., 2006. Variation in organic-carbon concentration and bulk density in Flemish grassland soils. Journal of Plant Nutrition and Soil Science 169, 616—622.

NEN 5754, 2005. Soil-Determination of organic matter content in soil and sediment as loss-on-ignition. http://www2.nen.nl/nen.

Oenema, O., Berentsen, P.B.M., 2004. Manure Policy and MINAS: Regulating Nitrogen and Phosphorus Surpluses in Agriculture of the Netherlands. OECD report COM/ENV/EPOC/CTPA/CFA 2004, 1–67.

Rosell, R.A., Casparoni, J.C., Galantini, J.A., 2001. Soil organic matter evalution. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Assessment Methods for Soil Carbon. In: Advances in Soil Sciences. CRC Press, Boca Raton, Boston, pp. 311—322.

Saby, N.P.A., Bellamy, P.A., Morvan, X., Arrouays, D., Jones, R.J.A., Verheijen, F.G.A., Kibblewhite, M.G., Verdoodt, A., Üveges, J.B., Freudenschuss, A., Simota, C., 2008. Will European soil-monitoring networks be able to detect changes in topsoil organic carbon content? Global Change Biology 14, 2432—2442.

Schroder, J.J., Neeteson, J.J., 2008. Nutrient management regulations in the Netherlands. Geoderma 144, 418—425.

Sleutel, S., De Neve, S., Hofman, G., Boeckx, P., Beheydt, D., Van Cleemput, O., Mestdagh, I., Lootens, P., Carlier, L., Van Camp, N., Verbeeck, H., Van De Walle, I., Samson, R., Lust, N., Lemeur, R., 2003. Carbon stock changes and carbon sequestration potential of Flemish cropland soils. Global Change Biology, 9, 1193—1203.

Smith, P., Powlson, D.S., Smith, J.U., Fallon, P., Coleman, K., 2000. Meetings Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Global Change Biology 6, 525—539.

Smith, P., Andren, O., Karlsson, T., Perala, P., Regina, K., Rounsevell, M., Wesemael, B., 2005. Carbon sequestration potential in European croplands has been overestimated. Global Change Biology 11, 2153—2163.

Stolbovoy, V., Montanarella, L., Filippi, N., Selvaradjou, S., Panagos, P., Gallego, J., 2005. Soil Sampling Protocol to Certify the Changes of Organic Matter Carbon Stock in Mineral Soils of European union, EUR 21576 EN, Office for Official Publications of the European Communities.

Van der Pouw, B., Finke, P., 1999. Development and perspective of soil survey in the Netherlands. In: Bullock, P., Jones, R., Montanarella, L. (Eds.), Soil Resources of Europe. European Soil Bureau Research Report 6. Office for Official Publications of the European Communities, Luxembourg.

Velthof, G.L., 2005. Input of organic matter to agricultural soils (in Dutch). Bodem 1, 11—13.

Vellinga, T.V., André, G., 1999. Sixty years of Dutch fertiliser experiments, an overview of the effects of soil type, fertiliser input, management and of developments in time. Netherlands Journal of Agricultural Sciences 47, 215—241.

Vellinga, Th.V., Van den Pol-van Dasselaar, A., Kuikman, P.J., 2004. The impact of grassland ploughing on CO_2 and N_2O emissions in the Netherlands. Nutrient Cycling and Agroecosystems 70, 33—45.

Visschers, R., Finke, F.A., De Gruijter, J.J., 2007. A soil sampling program for the Netherlands. Geoderma 139, 60—72.

Vleeshouwers, L.M., Verhagen, A., 2002. Carbon emission and sequestration by agricultural land use: a model study for Europe. Global Change Biology 8, 519—530.

Wadman, W.P., De Haan, S., 1997. Decomposition of organic matter from 36 soils in a long-term pot experiment. Plant and Soil 189, 289—301.

Yang, H.S., Janssen, B.H., 2000. A mono-component model of carbon mineralization with a dynamic rate constant. European Journal of Soil Science 51, 517—529.