Trends in carbon stocks in Dutch soils: datasets and modeling results

W.J. Chardon
H. Heesmans
P.J. Kuikman

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Observations on trends in soil organic carbon (SOC) in agricultural soils is an important basis for mandatory reporting of emission of greenhouse gases from land use. A decrease indicates that these soils are a source of CO_2, an increase that they are a sink. IPCC Good Practice Guidance generally assumes that the SOC content of agricultural soils decreases. We evaluated large datasets on trends in SOC in the Netherlands and compared them with datasets from Belgium, England and with literature in general. Also, the soil organic matter simulation model Century was used for a better understanding of soil processes related to manure application and SOC dynamics. The IPCC assumption of decreasing SOC contents was not confirmed for Dutch agricultural soils: on soils with SOC < 70 g/kg the SOC contents are constant or increase slightly. The large amounts of manure and fertilizers applied on agricultural soils in The Netherlands could explain this trend. The positive effect of manure on SOC from the calculation with Century is significant, but smaller than the calculated effect from using IPCC Guidelines for calculation of soil organic matter budgets in National Greenhouse Gas Inventories.

Keywords: soil; carbon stocks; modeling; trend

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Phone: + 31 317 480700; fax: +31 317 419000; e-mail: info.alterra@wur.nl

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Preface

The aim of this study was to develop a methodology and national reporting system for reporting soil carbon stocks and changes that fits the requirements set out by UNFCCC, and allows to report with the Common Reporting Format, and select and develop a calculation methodology for soil carbon stocks and soil carbon changes as result of land use and land use change.

The main results and products are:

- A methodology for calculating stocks and changes in soil carbon as result of land use and land use change that complies with UNFCCC requirements
- An approach on handling and reporting on grassland in the national inventory
- An inventory of methodologies and approaches used by neighboring EU countries
- The identification of and policy support on future developments

Summary

Any observations on trends in soil organic carbon (SOC) in agricultural soils are an important basis for reporting of emission of greenhouse gases as required by UNFCCC, the Climate treaty and the Kyoto Protocol. A decreasing SOC content indicates that these soils are a source of CO_2, an increasing content that they are a sink. IPCC Good Practice Guidance provides support and default methods and values to calculate any changes in soil organic matter. The methodology and default emission values lead to the IPCC assumption that the SOC content of agricultural soils generally decreases.

In this study large datasets on trends in SOC for the Netherlands have been evaluated and compared with datasets from Belgium, England and with literature results in general. Also, the soil organic matter simulation model Century was used to obtain a better understanding of soil processes related with application of animal manures, fertilization and SOC.

It was concluded that based on these datasets the IPCC assumption of generally decreasing SOC contents in agricultural soils is not confirmed for Dutch soils: on non-organic soils (SOC < 70 g/kg) the contents of SOC are constant or increase slightly. The large amounts of manure and fertilizers applied on agricultural soils in The Netherlands could explain this trend as high levels of primary production can be maintained. This will contribute to high input of organic materials from biomass growth to soils in the Netherlands. The calculated positive effect of manure on SOC is significant, but smaller than is calculated using IPCC Guidelines for National Greenhouse Gas Inventories.

1 Introduction

The Netherlands has signed the climate treaty, the United Nations Framework Convention on Climate Change (UNFCCC), and subsequently the Kyoto Protocol. It is therefore mandatory to report to the international community (UNFCCC) about the carbon stocks in the soil under different forms of land use and changes therein. The Netherlands has reported the carbon stocks for the first time 2005.

Within a national protocol the Netherlands has to report how carbon stocks are determined and how changes in the stocks are calculated as a part of internationally mandatory reporting. In 2002 and 2003 it was investigated how stocks can be determined and which databases are available for a Dutch monitoring system and which data are missing (see Kuikman et al., 2003; Nabuurs et al., 2003; Kuikman et al., 2004). In 2004 a reporting system was developed with a protocol and calculations were done on carbon stocks. Both have been reported by de Groot et al. (2005), and were used for a report to the secretariat of UNFCCC.

Objectives of this study
This study deals with temporal changes in carbon stocks of agricultural soils in The Netherlands, both in soils of which the use does not change with time and soils on which grassland and maize are alternated. Also, the influence of application of animal manure and other forms of organic matter to agricultural soils on changes in carbon stocks is discussed.

Methods used
A change in the amount of carbon in a soil profile indicates that the soil either acts as a sink for CO_2, (amount of C increases), or as a source (amount of C decreases). For estimating if changes in the amount of C in Dutch soils are likely to occur, three methods were used :

- Evaluation of datasets on changes in soil organic matter content.
- The use of simulation models.
- Evaluating the consequences of (expected) changes in land use.

Results of these three methods are presented in the following paragraphs.

2 Calculation of SOC changes according to IPCC method

Within volume 4 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006) a method is given for the estimation of the default amounts of soil carbon; also, coefficients are given for land use, management and input to crop production. The actual amount of soil organic carbon (SOC) can be calculated as:

$$SOC = SOC_{REF} * F_{LU} * F_{MG} * F_{I} = SOC_{REF} * FFF \quad [1]$$

with:

SOC_{REF} = reference carbon content of the soil (ton C per ha, 0-30 cm)
F_{LU} = coefficient for land use
F_{MG} = coefficient for management
F_{I} = coefficient for input crop production
FFF = $F_{LU} * F_{MG} * F_{I}$

Table 1 gives (default) values for F_{LU}, F_{MG}, F_{I} as given in IPCC (2006), table 5.5 for cropland (long-term cultivated, temperate and moist, under full tillage), and in table 6.2 for grassland (nominally managed [non–degraded] or improved temperate grassland. Also, in table 1 the values are given of the C-stock, calculated according to equation [1], 20 years after land use change has occurred. For this calculation, values of SOC_{REF} were used as given in table 2.3 of IPCC (2006).
Within equation 1, the product $F_{LU} * F_{MG} * F_{I}$ determines the change that is assumed to occur during the first 20 years after land use change. For cropland, the values of F_{LU}, F_{MG} and F_{I} in table 1 slightly differ from the values given in IPCC (2003), leading to a change in the calculated carbon stock for arable soils. Deviations between IPCC 2003 and 2006 are shown in Appendix 1 of this report.

For the use as cropland without return of residues this product amounts 0.63 (table 1), and with return of residues 0.69. This corresponds with a decrease in SOC of (100*[1-0.63]=) 37% and 31%, respectively (or 37/20=1.85 and 31/20=1.55 % yr^{-1}). Only when residues are returned and also manure is added, it is calculated that SOC decrease on cropland is negligible ($F_{LU} * F_{MG} * F_{I} = 0.99$).

Using the data for arable land in Table 1, it can be calculated what the (assumed) effect is of manure application on SOC stocks. Under “High (all res. – manure)” and High (all res. + manure)” values for SOC stock of resp. 54 and 71 ton/ha are found for sand, and 71 and 94 for clay soil. The differences are the result of 20 years cropping at high input of nutrients, with or without manure application; they correspond with resp. 808 and 1082 kg C/ha/yr. Unfortunately, no data are given by IPCC (2006) for the size of the “regular addition of animal manure” that is assumed to be applied yearly in their calculation of the effect. If this would be 10 ton/yr the SOC increase would correspond with 81 kg C/ton manure/yr for sand, and 108 kg C/ton for clay; if it is based on 20 ton/yr this would be 40 kg C/ton for sand, and 54 kg C/ton manure/yr for clay.

Table 1. Parameters used by IPCC (2006) for cropland and arable land for Dutch conditions, and calculated SOC stock changes using these parameters.

Cropland or Grass	Input via returned residues or via applied manure	FLU	FMG	FI	FFF [1]	ST [2]	SOC [3]	ΔSOC / yr [4]		
							ton C/ha	ton/ha	% [5]	g/kg [6]
Cropland [7]	Low (no residues)	0.69	1.00	0.92	0.63	s	45	-1.30	-1.83	-0.33
						hac	60	-1.73	-1.83	-0.44
	Medium (all residues)	0.69	1.00	1.00	0.69	s	49	-1.10	-1.55	-0.28
						hac	66	-1.47	-1.55	-0.38
	High (all res. – manure)	0.69	1.00	1.11	0.77	s	54	-0.73	-1.17	-0.21
						hac	73	-1.11	-1.17	-0.29
	High (all res. + manure)	0.69	1.00	1.44	0.99	s	71	-0.02	-0.03	-0.01
						hac	94	-0.03	-0.03	-0.01
Grass [8]	Nominally, medium/high	1.00	1.00	1.00	1.00	s	71	0	0	0.00
						hac	95	0	0	0.00
	Improved, medium	1.00	1.14	1.00	1.14	s	81	0.50	0.70	0.13
						hac	108	0.66	0.70	0.17
	Improved, high	1.00	1.14	1.11	1.27	s	89	0.94	1.33	0.24
						hac	120	1.26	1.33	0.32

[1] FFF = FLU * FMG * FI

[2] Soil Type, both cold temperate and moist. Sandy soil (s) (SOC_{REF} = 71 ton C in 0-30 cm) or soil with high activity clay (hac) minerals (SOC_{REF} = 95 ton C in 0-30 cm). Data SOC_{REF} : IPCC (2006), table 2.3.

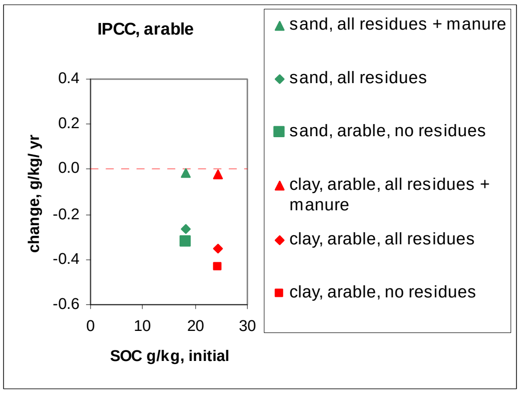
[3] SOC-stock, calculated 20 years after land use change has occurred, according to equation [1]

[4] Yearly change in SOC-stock; [5] as % of SOC_{REF}; [6] as g/kg, layer 0-30 cm, bulk density 1.3 kg/L

[7] Long-term cultivated, full tillage, temperate, moist cropland

[8] Nominally managed (= non–degraded) or improved temperate grassland

The values calculated in Table 1 for yearly SOC change are plotted in Figure 1: left for arable land, and right for grassland.



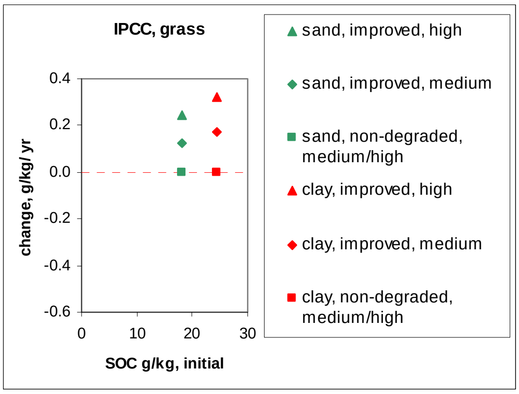


Figure 1. Changes in SOC in plough layer, calculated using IPCC (2006) parameters, see Table 1.

For use as nominally managed (= non–degraded) grassland the product equals 1, so no decrease in SOC is assumed, and for improved grassland with medium input: 1.14 (14% increase or 14/20=0.7 % yr^{-1}), and for high input 1.27 (27% increase or 27/20=1.35 % yr^{-1}).

Concluding: when the default coefficients of IPCC (2006) are used, large differences in development of SOC during 20 years of agricultural practices are calculated, varying from -1.85% (cropland) to +1.3% (grassland) of initial SOC per year. However, based on the results of a pot experiment where changes in soil organic matter content were followed for 18 soils during 20 years (Wadman and De Haan, 1997), it was concluded that relative decomposition rates decreases with time, and that a constant rate should thus not be used. The decomposition rate decreased more when the initial organic matter content was lower, which was ascribed to a relatively larger amount of fresh organic matter at a lower initial OM content. Also, from modeling results for long-term experiments in literature (Smith et al., 1997b; Heesmans and De Willigen, 2009) it was concluded that changes in SOC during the first 20 or 40 years are always much larger than after e.g. 50-80 years.

In most European countries the major land use changes occurred much longer than 20-30 years ago, and recent trends are more towards conversion of arable land to other land uses (Janssens et al., 2004). In The Netherlands, most changes from natural grassland or heather have occurred more than 80 years ago. This can be derived from the decrease of the surface of open natural land ("woeste grond"). This was in 1900 16% of the total land surface, in 1939 8%, and in 1975 5%, after which it more or less stabilized (Berkhout and Van Bruchem, 2008). The total land surface in The Netherlands equals 3.4 M ha, and if the open natural land was all converted to agricultural land, these figures indicate that between 1900 and 1936 (3.4*[0.16-0.08]=) 0.27 M ha agricultural land was developed, and between 1938 and 1975 this was (3.4*[0.08-0.05]=) 0.10 M ha.
For the total surface of agricultural land (1.9 M ha) in The Netherlands this means that:

- [1.9-0.27-0.10=] 1.53 M ha (81%) was converted from natural areas more than 108 years ago (before 1900);
- [1.9-0.10=] 1.80 M ha (95%) before 1918 (average of 1900 and 1936), so more than 90 years ago;
- only 5% has an age of between 33 and 70 years.

This implicates that the IPCC coefficients that lead to an estimated strong decrease of SOC in the first 20 years of agricultural land use should probably be considered as a "worst case scenario", and do not represent current developments in SOC stock in agricultural soils in The Netherlands.

In the following chapter datasets on the development of SOC from The Netherlands are discussed, and they are compared with datasets from Belgium and England and Wales.

In chapter 4 results from model calculation using the CENTURY model are discussed, and in chapter 5 a comparison is made between IPCC data, CENTURY model calculations, and field data.

3 Evaluation of datasets on changes in soil organic matter content

In a number of recent papers datasets of soil sampling were evaluated, and trends in SOC contents on a regional or national scale were found. In the following paragraphs results are summarized from The Netherlands, Belgium, England and Wales.

3.1 The Netherlands

In a paper by Reijneveld et al. (2009), data from a database with 2 million results of soil analysis from farmers' fields were analyzed; within this, 304 000 data on SOC were available. All samples were taken and analyzed by one laboratory (BLGG in Oosterbeek) during the period 1984-2004. Three land use types were distinguished: arable land, grassland and maize land. All data were grouped in nine specific regions and were analyzed for trends in SOC over time and for differences between regions. Figure 2 shows the trends for the 13 combinations of region and land use type.

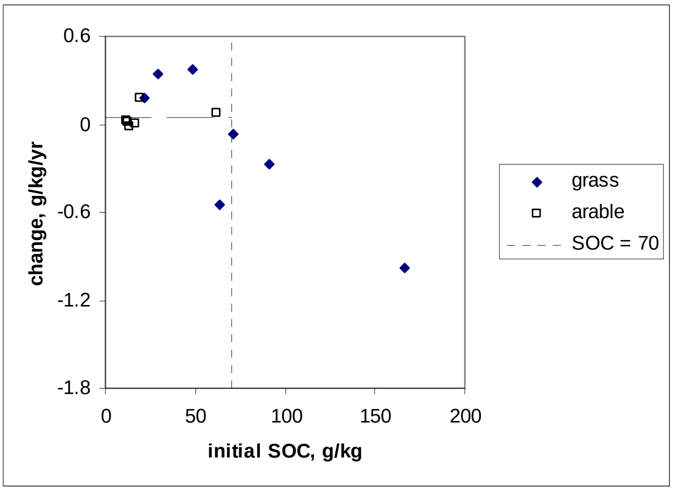


Figure 2. Change in SOC in grassland and arable soils in 13 different combinations of region, soil type and crop from The Netherlands in the period 1984-2004. Data from Reijneveld et al. (2009). The horizontal line shows the weighted (based on the number of samples for the region during 1984-2004) average trend for categories with SOC_{in} < 70 g/kg (0.051 g/kg/yr).

From this figure it can be seen that 10 combinations fall in the SOC_{in} range of 0-70 g/kg; a horizontal line shows the weighted average trend for these combinations, an increase of 0.051 g/kg/yr (0.089 g/kg/yr for the 4 grassland combinations, and 0.032 g/kg/yr for the 6 arable combinations). Nine out of these 10 (94% of the samples) show either no change or an increase in SOC during the period 1984-2004; only one (grassland on marine clay, 6% of the samples) shows a decrease in SOC. It can thus be concluded that for non-organic (SOC <70 g/kg) agricultural soils the SOC

content did not change, so no emission of CO_2 takes place due to a decrease in SOC in these soils.
Three combinations (grassland on reclaimed peat and arable land on peaty clay in North and West NL) had an SOC_{in} of 70 g/kg and higher. These three show a decrease in SOC during this period, the effect is stronger when SOC_{in} was larger.

Hanegraaf et al. (2009) performed a trend analysis of SOM contents in sandy soils, sandy loams or loamy sands, using data from the same database as used by Reijneveld et al. (2009). Data were taken for fields in four adjacent provinces (Drenthe, Overijssel, Gelderland and Noord-Brabant), that were sampled 4-5 times during the period 1984-2004. They found that in more than 75% of all fields the level of SOM remained stable or increased, whether used for permanent grass, a grass-maize rotation or continuous maize.

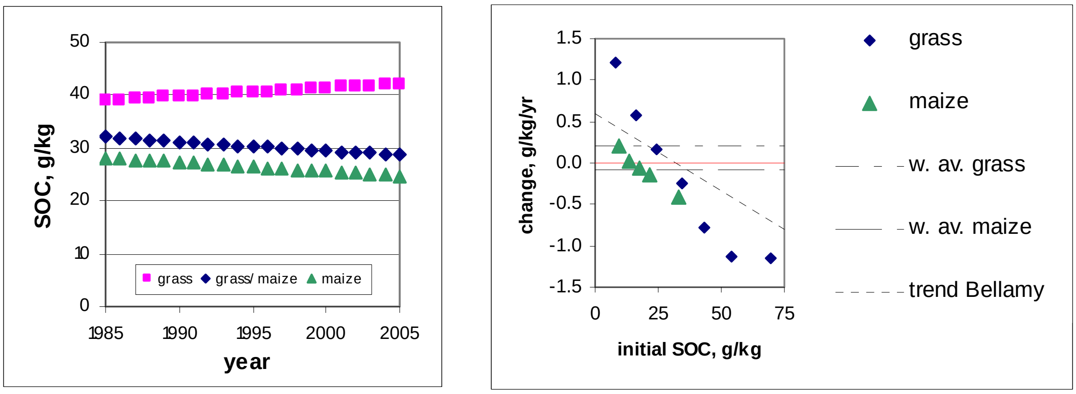


*Figure 3. Left: trends of SOC under grassland (0-5 cm), a grass (0-5 cm) - maize (0-25 cm) rotation or continuous maize (0-25 cm), on sandy soils in the Province of Drenthe (NL). Right: relationship between initial SOC content and absolute changes in sandy soils with grass or maize in the Province of Noord-Brabant (NL). The horizontal lines show the average trend, weighted based on the number of samples for the category of initial SOC content. Data for the period 1984-2004, after Hanegraaf et al. (2009, their figs. 2 and 5 respectively). SOC content (g/kg) was estimated as: 10*0.5*SOM (%).*

Figure 3, left, shows a positive trend for SOC in grassland soils in the Province of Drenthe, and slightly negative trends for a grass-maize rotation and for continuous maize. Figure 3, right, shows absolute changes of SOC, as a function of initial SOC content, for grass and maize fields maize in the Province of Noord-Brabant. The absolute changes were linearly correlated with the initial SOC content, as was also found by Bellamy et al. (2005), see also the line in the figure. On grassland the absolute changes were larger than found by Bellamy, which is probably caused by the fact that Hanegraaf et al. (2009) used data for the 0-5 cm layer for grassland, while Bellamy used data for the 0-15 cm layer. For grassland a weighted average trend of + 0.205 g/kg can be calculated, and for maize a trend of -0.082 g/kg/yr.
Hanegraaf et al. concluded that their analysis does not support the prevailing opinion in Europe that SOM content in agricultural land is declining, corresponding with the findings of Reijneveld et al. (2009). Another conclusion was that no uniform trend was present in grassland sandy soils, and that this cannot be expected in the near future. In each of four different regions, SOM trends were diverse (i.e. decreasing, stable or increasing) (Hanegraaf et al., 2009).

3.2 Belgium

Changes in soil carbon stocks of Flemish cropland soils were calculated by Sleutel et al. (2003) for the period 1989-2000. Their estimation was based on 190 000 soil organic carbon (SOC) data that were collected for the 0-24 cm soil layer of farmers fields. Data were grouped based on soil texture and spatial location. The setup of this study was thus comparable with the study of Reijneveld et al. (2009). Figure 4 (left) shows for the 27 groups the calculated change in the SOC content, showing a large variability in the changes. Weight-averaged the mean decrease in SOC was -0.174 g/kg/yr; this value is shown in the summarizing table 2 and in Fig. 4 (right).
Lettens et al. (2005) compared data for SOC stocks in Belgium in 1960, 1990 and 2000. Data were grouped according to landscape units, with comparable soil type and land-use. For the period 1960-1990 an increase in SOC was found for both arable land and grassland; however, a decrease was found for both for 1990-2000 (table 2 and figure 4, right).

Table 2. Changes in SOC calculated in different studies for Belgium.

land-use	period	SOC_{in} g/kg	change g C/kg/yr	reference
arable	1955-2005	13.6	– 0.048	Goidts and Van Wesemael (2007)
arable	1960-1990	14.6	+ 0.013	Lettens et al. (2005)
arable	1989-2000	13.9	– 0.174	Sleutel et al. (2003)
arable	1990-2000	15.0	– 0.077	Lettens et al. (2005)
grass	1955-2005	16.0	+ 0.118	Goidts and Van Wesemael (2007)
grass	1960-1990	20.8	+ 0.128	Lettens et al. (2005)
grass	1990-2000	24.6	– 0.154	Lettens et al. (2005)

Goidts and Van Wesemael (2007) analyzed data from samplings using a regular grid in southern Belgium. Data from samples taken in 2005 were compared with data from 1955, so a change during a period of 50 years could be calculated. On average, for arable land they found a decrease of -0.048 g C/kg/yr, and for grassland an increase was found of 0.118 g C/kg/yr (table 2 and figure 4, right).

From these data it appears that the trends found for the period 1955-2005 (Goidts and Van Wesemael, 2007) or 1960-1990 (Lettens et al., 2005) differ from trends for the period 1989-2000 (Sleutel et al., 2003) or 1990-2000 (Lettens et al., 2005). During the first period losses on arable land are small or negligible, and on grassland a build-up takes place.

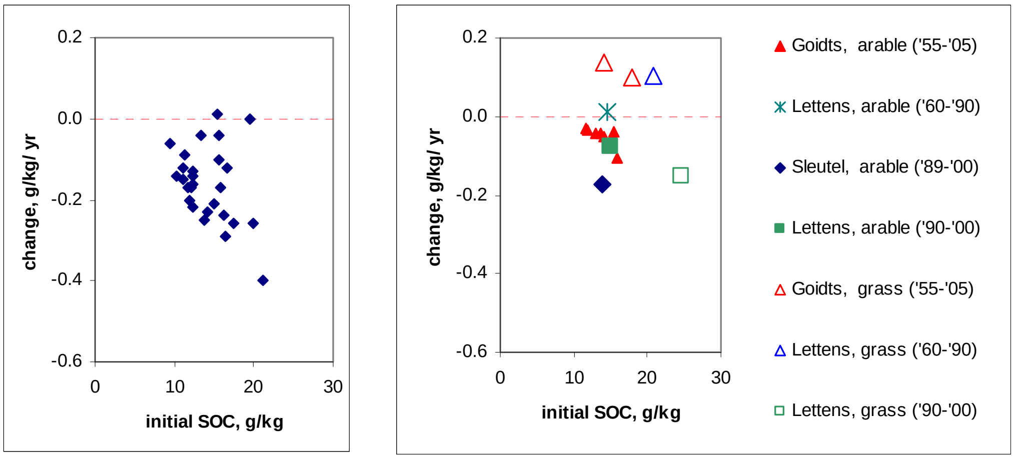


Figure 4. Left: change in SOC in Flemish arable soils in the period 1989-2000. Data from Sleutel et al. (2003). Right: changes calculated for grassland and arable soils by Goidts and Van Wesemael (2007), Lettens et al. (2005), and weighted average of Sleutel et al. (2003), calculated for different periods (1955-2005, 1960-1990, 1989-2000, and 1990-2000).

This decrease contrasts with findings by Heidmann et al. (2002, cited in Smith et al., 2007), who reported no decrease in SOC for Danish croplands, and Dersch and Boehm (1997, cited in Smith et al., 2007), who reported the same for Austrian soils. The relatively large decrease found in Belgium is ascribed to the restriction by law of the use of animal manure on cropland, starting in 1990 (Sleutel et al., 2003; Lettens et al., 2005; Goidts and Van Wesemael, 2007). Another possible explanation is that part of the cropland in 1990 was previously pasture, which had been brought into cultivation in the two preceding decades (Sleutel et al., 2007a). Also, erosion caused by intensified management on erodible arable land is mentioned as a possible cause of loss in SOC (Lettens et al., 2005).

In a more detailed analysis of the data, it was found that the change in % SOC was positively correlated with the number of livestock per ha cropland in different communities in the region Leuven (Sleutel et al., 2003, Fig. 5).

This implicates that a high animal density in a community had a positive influence on the change in local SOC, which can probably be explained by a larger amount of manure used per hectare.

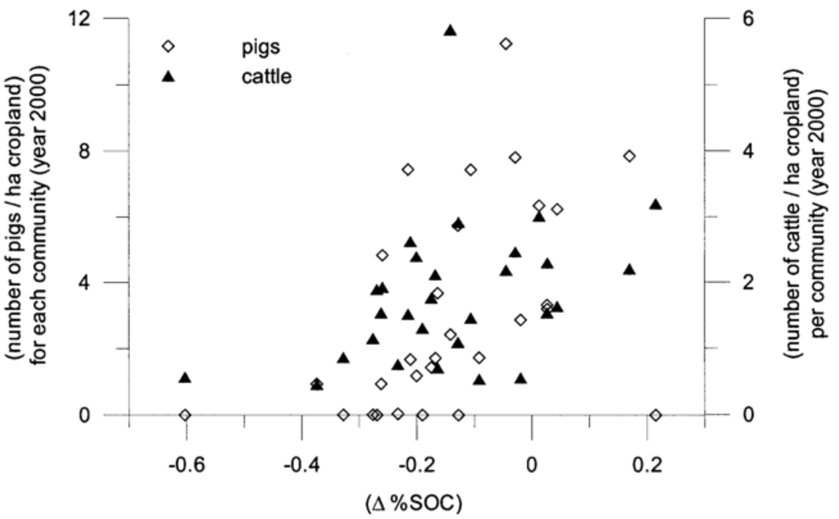


Figure 5. Scatter plot between the livestock density per community (number of livestock units per hectare cropland) in the Leuven district and the difference between the mean SOC content per community with the Flemish average SOC content of the corresponding textural class (Δ% SOC) *(from: Sleutel et al., 2003).*

3.3 England and Wales

For England and Wales, Bellamy et al. (2005) summarized SOC data from the 0-15 cm soil layer, determined between 1978 and 2003. The data were grouped on the basis of their original SOC content. Figure 6 shows the relation between the initial SOC content and the change in SOC during the period of study, for different ranges of SOC (0-20-30-50-100-200-300- g/kg). The left figure shows the absolute changes (g/kg/yr), the right figure the change as % of the mean original SOC. Note that the range in values of initial SOC is 20 times the range of the data shown in Fig. 4 for Flemish arable soils.

The absolute value of the change in SOC is strongly linear correlated with the initial SOC content; the equation for the line is:

$$\text{Rate of change in SOC} = 0.6 - 0.0187 \times SOC_{in}$$

The relative values (% of SOC_{in} per year) decrease very strongly with SOC_{in} in a non-linear way (Fig. 6, right).

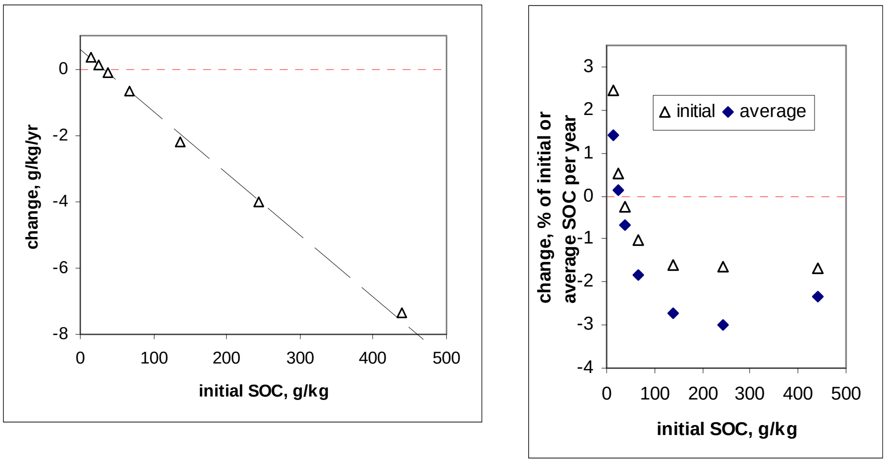


Figure 6. Change in SOC in soils from England and Wales in the period 1978-2003. Data from Bellamy et al. (2005). Left: absolute values, right: relative values, as % of initial SOC or of average SOC during sampling period (calculated by Bellamy).

In a paper by Smith et al. (2007), the results of Bellamy et al. (2005) were discussed. Several possible explanations were given for the decrease found by Bellamy et al.:

- A decrease in the number of animals, leading to less manure being applied
- More efficient removal of crop residues
- Increase in production of silage maize in place of hay, leading to removal of more residues and decrease in SOC
- Deeper ploughing depths, leading to more mineralization and diluting surface SOC levels
- Legacy effects of land use change occurring before 1978, effects of this are visible after more than 120 years.

According to Smith et al. (2007) these factors mentioned above cannot be excluded in the study of Bellamy et al. (2005), so can possibly explain (part of) their results. However, these factors can not explain the large decrease in mg/kg/yr (Fig. 6 left) of SOC in organic (peat) soils (Smith et al., 2007).

3.4 Discussion about datasets

In Fig. 7 the data (and trends) presented in the papers for The Netherlands, Belgium, and England and Wales are combined. From this figure and from Fig. 1 it is clear that on all arable soils from Flanders, and in 5 out of 6 regions in The Netherlands, the SOC content is very low when compared to most of the grassland soils in the Netherlands, and to most of the samples reported from England and Wales.

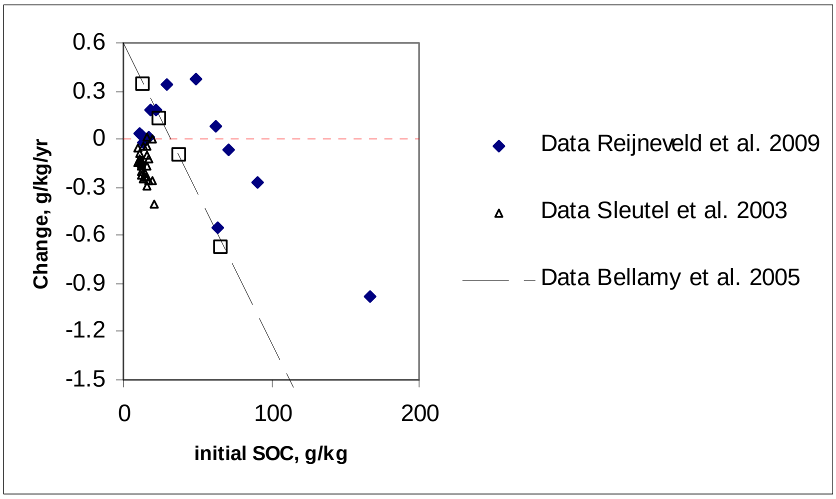


Figure 7. Change in SOC in soils from The Netherlands (1984-2004, Reijneveld et al., 2009), Flanders (1989-2000, Sleutel et al., 2003), and England and Wales (1978-2003, Bellamy et al., 2005).

What remains remarkable is that for most of the regions in The Netherlands a slight increase in SOC was found (Fig. 2) by Reijneveld et al. (2009). Also, Hanegraaf et al. (2009) found a constant or increasing SOC level in 75% of all fields between 1984 and 2004 (Fig. 3). This can possibly be explained by the large amount of manure applied in The Netherlands. The amount of manure that is allowed to be used has reduced in the Netherlands during the last decades (Chardon and Koopmans, 2004; Velthof, 2004, 2005). However, it still amounts to ca. 37 ton animal slurry/ha/yr under the current EU nitrate regulation for arable land, and 51 ton/ha/yr on grassland. According to the present Dutch derogation from the Nitrate Directive application limits for manure are resp. 180 and 250 kg N/ha/yr. For this calculation, an N-content of manure was used of 4.9 g N/kg (for cows; Velthof et al., 2000). Velthof (2004, 2005) estimated an average external input of effective organic matter, defined as the amount that is not decomposed 1 year after application to soil, of ca. 1000 kg/ha/yr; 90% of this amount comes from animal manure. Within The Netherlands, most OM (77%) originates from cattle, fattening pig and laying hens (Velthof, 2004). For these sources some data are summarized in Table 3. Cattle manure has an average OM content of 66 kg/ton (Mooij, 1996), and a fraction effective OM of 0.45 (Velthof, 2004). Thus, an effective OM amount of 0.45*66= 30 kg per ton manure is applied via cattle manure.

Table 3. Contribution to total OM supply via manure in The Netherlands, OM content and fraction effective OM for different types of manure.

Type of manure	% OM supply NL [1]	OM content kg/ton [2]	C content kg/ton [3]	Effective OM [4] %	Effective OM kg/ton
cattle	77	66	38	45	30
fattening pigs	11	60	35	30	18
laying hens	8	93	54	44	41

[1] Velthof (2004), p. 70-4; [2] Mooij (1996); [3] calculated as 0.58*OM; [4] Velthof (2004), p. 70-6

The weighted average content of effective OM for the three types of manure is 29 kg/ton. Using the Van Bemmelen factor of 58 % C in OM (Waksman, 1936; Nelson and Sommers, 1982) this gives 17 kg effective C per ton manure.

Smith et al. (1997a) reviewed 14 studies in which variable amounts of manure were added to soils in long-term field experiments. The SOC content in the 0-30 cm soil layer was determined for treatments with or without manure addition. From their data, the relative increase in SOC was calculated per ton manure applied per year; the results are presented in Fig. 8 (left). The calculated (absolute) yearly increase in the amount of SOC in the 0-30 cm soil layer per ton manure applied per year is also shown in Fig. 8 (right). For the 14 studies a (long term) average value was calculated of 12 (± 7) kg SOC /(ton.ha.yr). Using the regression line (y = -0.0789x + 17.6), yields at t=0 yr a value of 17.6, which corresponds very well with the value (17 kg C/ton) calculated above. The long term average of 12 kg SOC/ton corresponds with ca. 30% of C applied via manure (table 3).

Vleeshouwers and Verhagen (2001, 2002) used the CESAR simulation model for calculating the effect of application of manure on the SOC stock. For a yearly application of 35 ton/ha (Verhagen, pers. commun.) they calculated an increase with 1.5 ton C/ha, or 43 kg C/ton/ha. This estimation is ca. 3 times higher than the values derived from the data found by Smith (12-17 kg/ton).
Using the IPCC data presented in Table 1, it can be calculated what the assumed effect is of manure application. Unfortunately however, the assumed amount of manure applied is not given in the IPCC report. For 10 ton manure/ha/yr an increase of 81 kg C/ton manure/ha/yr is calculated for sandy soils, and 108 kg/ton for clay soils. For 20 (or 35) ton manure/ha/yr these data are 40 (or 23) kg/ton for sandy soils, and 54 (or 31) kg/ton for clay soils. Thus, it can be concluded that both the studies of Vleeshouwers and Verhagen (2001, 2002) and the IPCC data tend to over-estimate the positive effect of manure application on soil carbon content.

Tian et al. (2009) investigated strip-mined loamy soils that had received biosolids from wastewater treatment during a period between 8 and 23 years. From the data of cumulative C applied and SOC sequestered (their table 5), it can be calculated that, on average, 27% (±7%) of C applied had remained in the soil. This value corresponds well with the 30% mentioned above.

From Fig. 8 (right) it appears that the SOC increase showed a tendency to decrease when the period during which manure was added increased. This corresponds with the trend found by De Willigen et al. (2008) who compared several simulation models. When the models simulated a repeated addition of organic matter to a soil, all models predicted a decreasing effect with time of the added C on the SOC content. This may be explained by a gradual saturation of soil clay particles that are assumed to protect organic matter against decomposition (Hassink and Whitmore, 1997; Six et al., 2002).

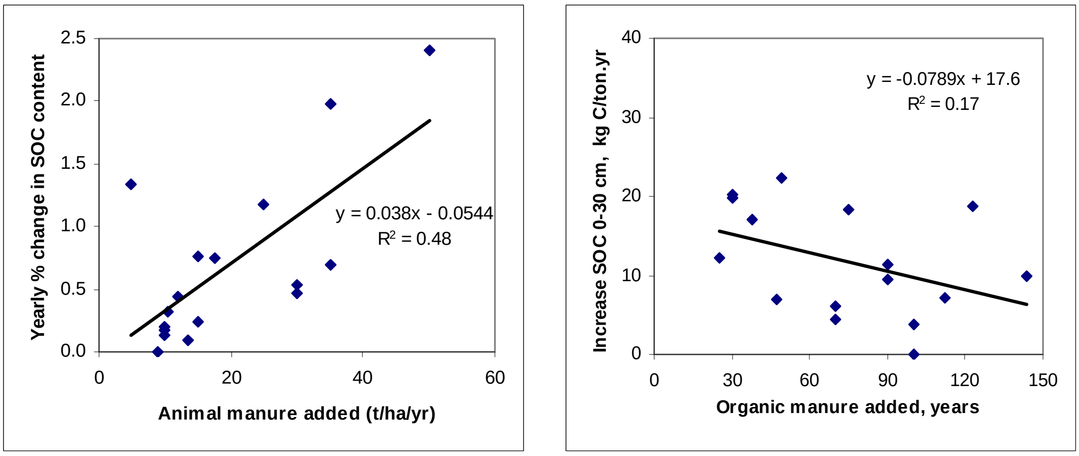


Figure 8. Left: influence of the amount of animal manure added on the yearly change in SOC in 16 plots from long-term field experiments, reviewed by Smith et al. (1997a, their table 3). Right: influence of the duration of the experiment on the measured yearly increase in the amount of SOC in the layer 0-30 cm (kg C per ton manure/ha.yr)

The regression equation shown left in Fig. 8 was used to estimate the predicted increase in SOC (% of SOC_{in}) for different amounts of manure used. In Fig. 9, left, these predictions were compared with the data found by Reijneveld et al. for the yearly increase in SOC, also expressed as % of SOC_{in}.
From this figure it can be seen that the relative increase in SOC in 8 out of 13 regions in The Netherlands can probably be explained by addition of 20-40 ton manure/ha/yr. These are amounts that were very common in the past, especially on sandy soils in Southern and Eastern parts of The Netherlands.

From the data of Reijneveld et al. (2009) the increase in SOC can also be calculated in ton C/ha/yr, these data are shown on the right-hand-side in Fig. 9. For the different regions this amount varied between -0.6 and +0.6 ton C. For grassland soils in European countries, Janssens et al. (2004) calculated a range for the C-balance between -0.5 and +1.7 ton C/ha/yr (average +0.6 ton). For arable soils they calculated an average loss of 0.6 ton C/ha/yr.
For soils with an initial SOC of < 70 g/kg, a weighted average increase of 0.064 ton C/ha/yr was calculated for the data of Reijneveld. Using the value for the 14 studies of Smith et al. (1997a) of (on average) 12 kg SOC /ha/yr per ton manure applied yearly, the weighted average increase of 0.064 ton corresponds with only 5.3 ton manure/yr, which is a very small amount for Dutch agricultural practices. Fig. 9 (right) also shows lines calculated for the application of 10, 20 or 40 ton/yr of manure, using the value of 12 kg C/ton. It appears that for most regions the increase in SOC as calculated by Reijneveld et al. (2009) can be explained by the application of not more than 20 ton manure/ha/yr.

A consequence of application of large amounts of manure is that agricultural soils will contain a relatively large proportion of 'young' organic matter. When the amount of manure applied decreases strongly, e.g. due to regulation, this may lead to a decrease in SOC (Smith et al., 2007). This was assumed to explain results found in Flanders, and can possibly also explain the decrease in SOC found for maize soils by

Hanegraaf et al. (2009). In the past, maize received very large amounts of manure, since maize is the only crop that is able to endure large amounts of manure without growth reduction. In The Netherlands, it is considered to change fertilizer application rates in such a way that no more phosphorus may be applied when the availability in the soil is high. This will be the case on soils that received excessive amounts of manure in the past. When further application of phosphorus is not allowed, this implicates that no more manure can be applied either. On these soils a decrease in SOC will be inevitable in the future.

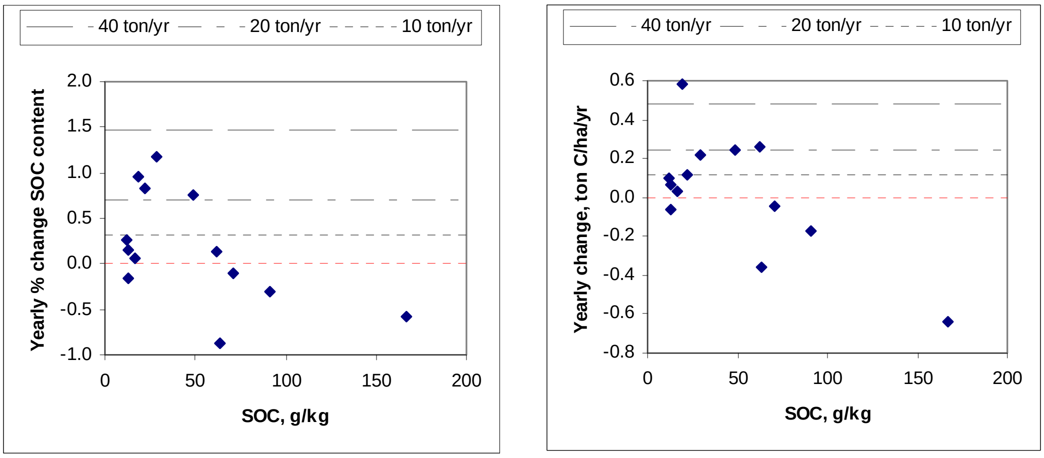


Figure 9. Left: relative change in SOC in grassland and arable soils in 13 different regions from The Netherlands in the period 1984-2004 (data from Reijneveld et al., 2009). Drawn lines correspond with the equation derived from the data from Smith et al. (1997a), see Fig. 8. Right: absolute change of SOC, for the same regions; the drawn lines are calculated with the average value of 12 kg SOC / ha/ yr per ton manure applied per year.

4 The use of the Century simulation model

The factors management, soil texture, climate and SOC content have the largest influence on SOC dynamics and they exhibit a strong spatial variability (Sleutel et al., 2007a). Since SOC storage is controlled by this variety of biogeophysical, climatic, and management factors dynamic SOM models (e.g. Roth-C, CENTURY and DNDC) which integrate the main mechanisms governing SOC turnover are the most suitable tools for predicting changes (Paustian et al., 1997; Sleutel et al., 2007a). Now, simulation models are indeed widely used for understanding long-term processes in soils, and more recently, to predict the influence of management practices on the changes in SOC that can be expected (Paustian et al., 1992, 1997; Sleutel et al., 2006a, 2006b; Smith et al., 1997b, 2007). For this purpose, different types of models are used: besides the more complicated dynamic models, also simple models like e.g. Minip (De Willigen et al., 2008).
For predicting development of SOC under Dutch conditions we have chosen the Century model (Parton et al. 1987), since it is widely used. Also, after comparing several models, De Willigen et al. (2008) concluded that the Century model was the only model that could reproduce organic matter contents that are currently found in soils from the Netherlands. Adapting existing datasets for Dutch conditions and searching for Dutch datasets that can be used for validation was a too timely effort, so a true validation on Dutch experiments was not possible. However, based on recent literature in which the Century model was applied under Western European conditions it was concluded that the model is also applicable for The Netherlands (Heesmans, 2007). Data and figures in this paragraph were taken from Heesmans (2007) or from Heesmans and De Willigen (2009).

4.1 Choose of parameters and initialization

For the model runs, a distinction must be made between the runs for the initialisation of Century, and the actual simulation. The initialization was not meant to reproduce Dutch reality, but only to reach a steady state for the SOM pools in Century. The initialization was a natural grassland environment which ran for 4000 years under three textures: sand, loamy sand and clay, and with Dutch weather data. Conditions were chosen such that the equilibrium conditions of SOC were comparable with data from an inventory (LSK and LGN) from Dutch soils. The initialization is consistent with Parton et al. (1993), who ran Century for 5000 years; the steady state levels of SOC of the long term runs were used as initial conditions for the validation study.
Figure 10 shows examples of initialization runs, showing a large build-up of SOC on the clay soil, and a smaller amount on the sandy soil. This is caused by the fact that clay 'protects' organic matter against mineralization. (Hassink and Whitmore, 1997; Six et al., 2002).

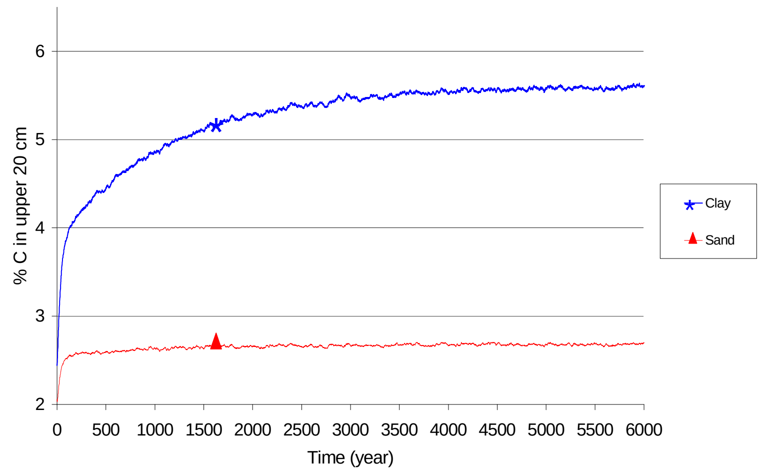


Figure 10. Build-up of total SOC during 6000 years of permanent grassland on clay and sandy soil. The x-axis shows the time after the run has started (in years).

Thus, clay soils under the same climate and similar management will tend to retain more SOC than sandy soils, and clay soils form a larger potential sink for CO_2. This was further investigated with the CENTURY model by De Willigen et al. (2008), (see figure 11), who found the relation:

$y = 0.8\ x + 2$ with y = equilibrium SOC (g/kg), and x = % clay.

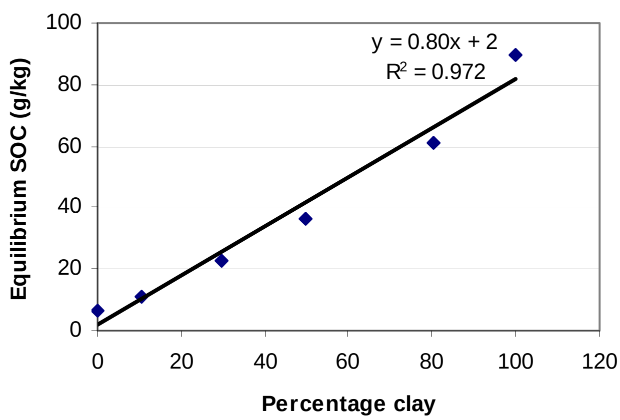


Figure 11. Equilibrium values of soil organic C (SOC), with an annual supply rate 382 g C m-2, as a function of clay content. Calculated using CENTURY (De Willigen et al., 2008).

Figure 12 shows how SOC develops under common agricultural rotations, from the moment that the original permanent grassland is taken in agricultural production. The rotations used were: maize-grass on sandy soil and wheat-potato-clover-sugar on the clay soil. The figure shows that after the conversion a strong decrease is predicted in the SOC: from 5.6 to 5.0 % in 30 years, and to 4.5 % in ca. 100 years for the clay soil, after which SOC decreases more slowly. In Table 4 the decrease in % SOC in the layer 0-20 cm is recalculated to the yearly loss of C (kg/ha), using as soil density of 1.3 kg/L. For the sandy soil the prediction is a decrease from 2.7 to 1.9 % in the first 100 years. This corresponds with the statement of Smith et al. (2007) that land-use changes can have a long-lasting effect on SOC. However, the decrease during the period 0-30 years is 3-5 times larger than during the period 30-100 years after land-use change. After 100 years, a decrease of less than 10 kg/ha.yr is predicted, which is less than the increase in SOC that was calculated for application of one ton manure per hectare/yr.

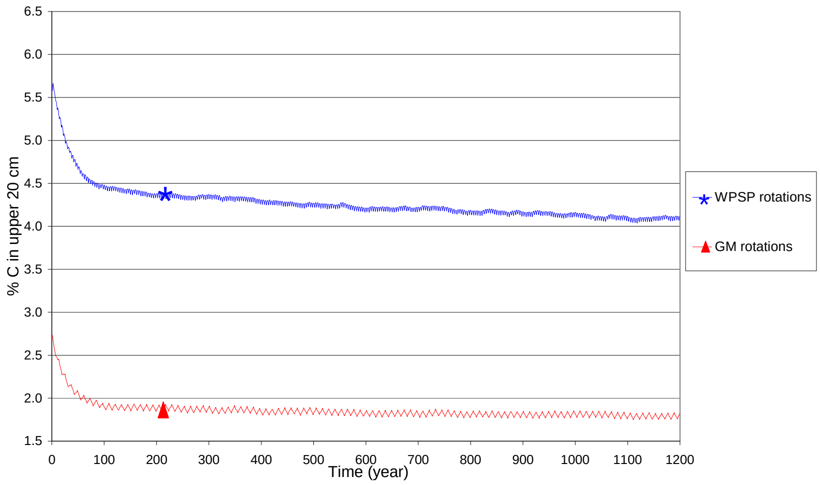


Figure 12. Total SOC under common agricultural rotations of grass-maize (GM) on sandy soil and winter wheat-potato-clover-sugar beet and potato (WPSP) on clay soil. The x-axis shows the time in years after the rotation has started (Heesmans, 2007).

Table 4. Decrease in SOC during different periods after agricultural rotations have started, calculated using CENTURY model (layer 0-20 cm, kg C/ha.yr; estimation based on figure 12).

Period, year	0-30		30-100		100-1200	
Soil type	%	kg C/yr	%	kg C/yr	%	kg C/yr
Clay	0.6	520	0.5	186	0.4	9
Sand	0.8	690	0.2	74	0.3	7

The actual simulations were the runs in which common Dutch agricultural rotations were simulated for 20 years. Based on Dutch literature, four options were chosen as rotations:

- permanent grass on sandy or clay soil (renewed after either 5 or 15 years);
- grass-maize rotation (4:2 or 3:3) on sandy or clay soil;
- permanent wheat on clay soil;
- wheat-potato-sugar beet-maize-grass rotation on sandy, loamy sand or clay soil.

Parameters were adapted according to Dutch literature data and the time span for the different runs was chosen in order to let all SOM pools be able to respond to the management changes.

Simulations were performed for 2 examples of soils from three texture classes (clay, loamy sand and sandy soil). Texture of soil 1 was based on the most extreme values for that class, texture of soil 2 on average values for the corresponding soil class. The textures of the mineral part of the soil for the 6 soil types used are summarized in table 5.

Table 5. Textures of soil types used in simulations with the Century model

Soil type	Soil	< 2 µm	2-63 µm	> 63 µm
		%	%	%
Clay	1	75	18	7
	2	25	55	20
Loamy sand	1	20	75	5
	2	8	50	42
Sand	1	4	26	70
	2	8	42	50

Table 6 gives the calculated SOC values at the end of the initialization period, so at the beginning of the simulated period of cropping. As mentioned before, conditions were chosen such that the equilibrium conditions of SOC were comparable with data from an inventory (LSK and LGN) from Dutch soils.

Table 6. SOC contents (g C/kg) of soils for different rotations, at the beginning of the simulated cropping period (average values for soil 1 and 2)

Rotation	SOC values at begin of cropping period		
	Clay	Loamy sand	Sand
Permanent grass	44		41
Grass / maize	35		21
Permanent grain	30		
Arable rotation	30	20	47

For the different soil types and rotations simulations were done, with or without an assumed application of manure. The amount of manure applied was based on the maximum allowed according to the Dutch regulation on nitrogen application via manure. This varies from 170 kg N/ha.yr for arable land to 250 kg N for permanent grassland. Figure 13 summarizes the main results of the simulations.

For an arable rotation on both loamy sand and clay soils a constant or slightly decreasing level of SOC is calculated when no manure is applied, and a slightly increasing level when manure is applied. However, for an arable rotation on sandy soil a strong decrease in SOC is calculated, even with manure application. For permanent grain (only simulated for clay soils), an almost constant SOC was calculated, with only a small influence of manure application.

For permanent grassland on clay soils an increase in SOC was calculated, even without manure application. On sandy soil however, a strong decrease of SOC under permanent grassland was simulated, even when manure was applied.

For a grass/maize rotation on clay soils a small decrease in SOC was calculated, and an increase with manure application. On sandy soil a decrease of SOC under grass/maize was simulated, and no change when manure was applied.

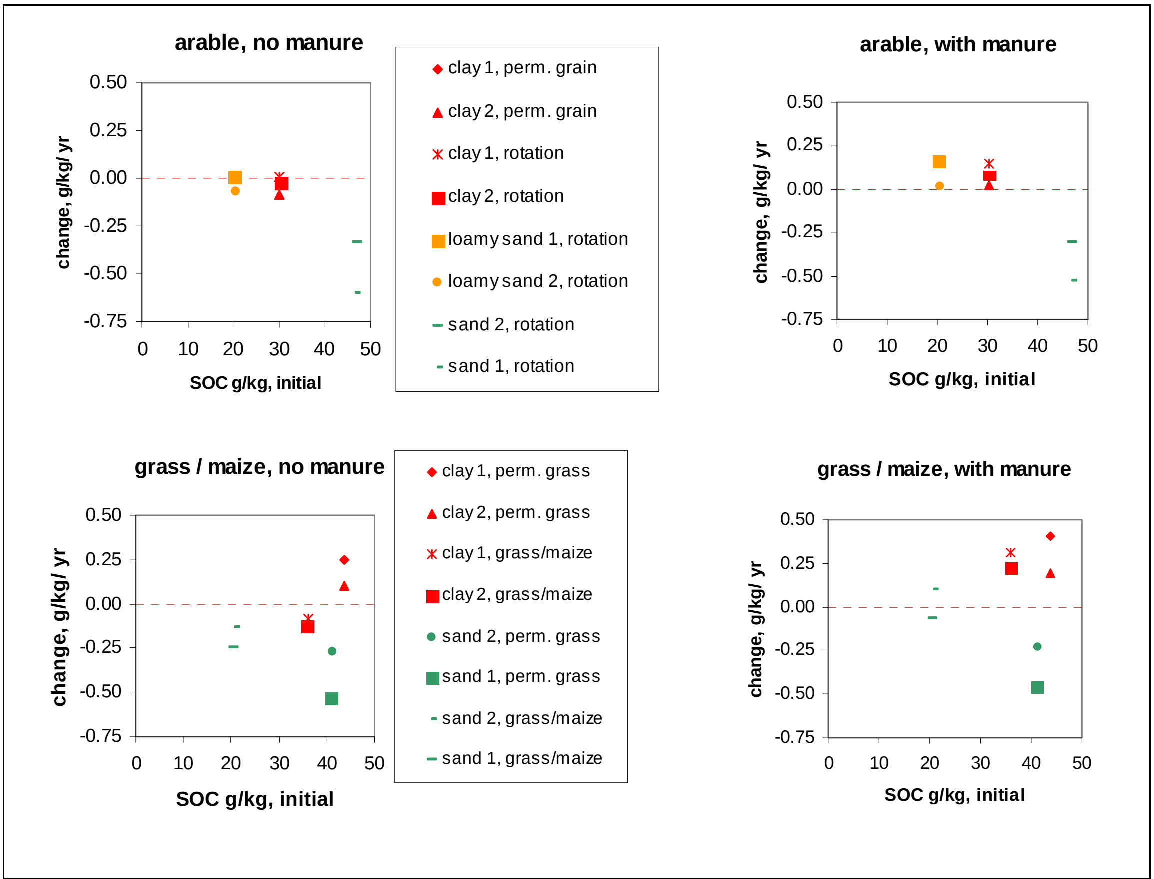


Figure 13. Simulated yearly change in SOC under permanent grass or a rotation of grass-maize on sandy or clay soils [bottom], or under permanent wheat or a wheat-potato-sugar beet-maize-grass rotation on sandy, loamy sand or clay soil [top]. Left: without application of manure, right: with manure (data Heesmans and De Willigen, 2009).

When interpreting the outcomes of the simulation shown in Fig. 13 it has to be kept in mind that the calculations were done for the first 20 years of agricultural production after land use change. As mentioned above, changes will probably be smaller when more time has passed after this change in land use. Nevertheless, Hanegraaf et al. (2009) found for sandy soils a comparable decrease in SOC at higher values of initial SOC (see figure 3, right).

The simulated positive influence of manure application on the amount of SOC in the plough layer is summarized in Table 7. Results are expressed as kg C in the layer 0-20 cm, per ton manure applied per year. As expected, the positive influence of manure application increases with clay content of the soil: sand < loamy sand < clay.

The calculated average values are plotted in Fig. 14, which also contains the data found by Smith et al. (see figure 8). From table 7 and Fig. 14 it appears that both the range and the average values for the soil types correspond well with the data found by Smith et al. (1997); from their review no influence of soil type could be derived.

Table 7. Simulated yearly change in SOC stock due to application of manure (kg SOC/ha per ton manure applied) in layer 0-20 cm for different soil types and rotations; range, average values and standard deviation (data Heesmans and De Willigen, 2009).

Soil type	Range	Average	St. dev.
Sand	2 - 21	9	8
Loamy sand	8 - 14	11	5
Clay	6 - 36	16	11

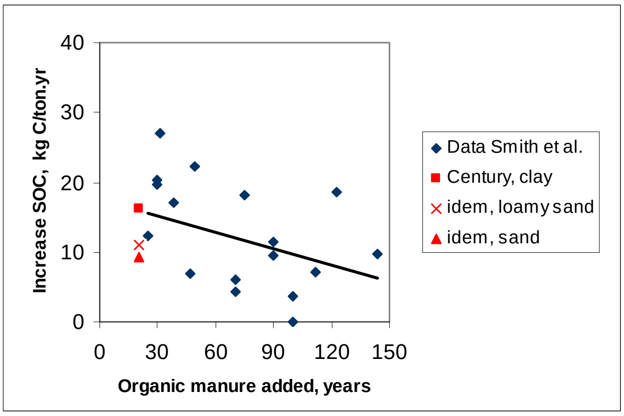


Figure 14. Simulated yearly change in SOC due to application of animal manure, expressed in kg SOC/ha per ton manure applied. Values calculated by Heesmans and De Willigen (2009) compared with data from Smith et al. (1997).

5 Evaluation

The results discussed in the previous chapters can be divided into three topics:

1. trends in arable soils;
2. trends in grassland soils;
3. positive effect of manure application on SOC.

ad 1. Trends in arable soils
For cropland with a high input via returned residues the IPCC method calculates a yearly SOC loss on sandy soil of 0.73 ton/ha when no manure is applied, and of 0.02 ton when it is applied; for clay soils these data are 1.11 and 0.03 ton. Janssens et al. (2004) calculated a yearly loss of 0.5 ton/ha for different European countries, irrespective of manure application. Thus, the data by Janssens correspond with the average of IPCC calculations for situations on sand and clay soils with and without manure. From the data of Reijneveld et al. (2009) a small increase of 0.032 ton C/yr could be calculated for the 6 arable combinations of region and soil type. From the data on maize land in Noord-Brabant, published by Hanegraaf et al (2009), a weighted average loss of 0.3 ton C/ha/yr can be calculated. Silage maize is a crop known to cause a decrease in SOC.

ad 2. Trends in grassland soils
For improved grassland with a high fertilizer input the IPCC method calculates a yearly SOC increase on sandy soil of 0.94 ton/ha; for clay soils this is 1.26 ton/ha. Janssens et al. (2004) calculated a range between -0.5 and +1.7 ton C/ha/yr for different European countries, with an average value of 0.6 ton. Thus, the average value of Janssens is slightly lower than the IPCC calculations. From the data of Reijneveld et al. (2009) a small increase of 0.089 g/kg/yr could be calculated for the 4 grassland combinations of region and soil type. From the data on maize land in Noord-Brabant, published by Hanegraaf et al. (2009), a weighted average increase of 0.09 ton C/ha/ yr can be calculated. Thus, both from Dutch data published by Reijneveld et al. and Hanegraaf et al. a small increase in SOC on grassland can be calculated, but this is smaller then the estimations made by IPCC and Janssens et al.

ad 3. Positive effect of manure application on SOC
From the IPCC data a positive influence of more than 40 kg C/ha can be calculated per ton manure applied. Vleeshouwers and Verhagen (2001, 2002) simulated a value of 43 kg C/ton. However, based on a study by Smith et al. (1997) and calculations using Century, it is estimated that a value between 10 and 20 kg C/ton manure is more realistic. Also, the positive influence of manure application tends to decrease when it is applied for a longer period, probably due to saturation of clay particles that protect SOC against mineralization.

It is thus concluded that for the majority of the mineral and non-organic agricultural soils (< 70 g SOOC/kg), the SOC content is either constant or even increases, and in a few cases (soil type with specific land use) may decrease a little. In the absence of a detailed monitoring system, it is considered fair and conservative to conclude that the SOC content of the Dutch agricultural soils overall does not change, so no net emission of CO_2 takes place due to a decrease in SOC in the soils in the Netherlands. The fact that agricultural soils in the Netherlands to a large extent maintain or even increase their SOC content is probably best explained by the relatively high amounts of animal manure and mineral fertilizer that is applied on these soils. This application leads to a build-up of SOC (Smith et al., 1997; Sleutel et al., 2006b).

As a consequence, within the Dutch National System for greenhouse gas reporting of the LULUCF sector , agricultural soils can be moved from Tier 1 (no stock change assumed) to Tier 2.

Conclusions

- No indications were found for a general decrease in SOC content in Dutch agricultural soils, so these soils are probably not a source of CO_2.

- On grassland soils only a small increase in SOC is found, but smaller than predicted by IPCC calculations or calculated by Janssens (2004) for European soils. Thus, grasslands in The Netherlands are not a large sink for CO_2.

- The fact that no decrease in SOC is found can probably be ascribed to the large amounts of manure (and other organic fertilizers) are applied in The Netherlands. If this application will be strongly reduced in the future there will be a risk of a local decrease in SOC.

- within the Dutch National System for greenhouse gas reporting of the LULUCF sector, agricultural soils can be moved from Tier 1 (no stock change assumed) to Tier 2.

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Appendix 1 Default values for FLU, FMG, FI as given in IPCC (2003)

Table 1 gives (default) values for F_{LU}, F_{MG}, F_I as given in IPCC (2003), table 3.3.4 for cropland (long-term cultivated, temperate and moist, under full tillage), and in table 3.4.5 for grassland (nominally managed [=non–degraded] or improved temperate grassland. From these tables, the GPG revised default values were used. Values in bold in the table differ from the values given in Table 1 from chapter 2; it can be concluded that differences are minor.
Also, in table 1 the values are given of the C-stock, calculated according to equation [1], 20 years after land use change has occurred. For this calculation, values of SOC_{REF} were used as given in table 2.3 of IPCC (2006).

Table 1. Parameters used by IPCC (2003) for cropland and arable land under Dutch conditions, and calculated SOC stock changes using these parameters. Figures in bold differ from IPCC (2006)

Cropland or Grass	Input via returned residues or via applied manure	F_{LU}	F_{MG}	F_I	FFF [1]	ST [2]	SOC [3]	ΔSOC / yr [4]		
							ton C/ha	ton/ha	% [5]	g/kg [6]
Cropland [7]	Low (no residues)	**0.71**	1.00	**0.91**	**0.65**	s	**46**	**-1.26**	**-1.77**	**-0.32**
						hac	**61**	**-1.68**	**-1.77**	**-0.43**
	Medium (all residues)	**0.71**	1.00	1.00	**0.71**	s	**50**	**-1.03**	**-1.45**	**-0.26**
						hac	**67**	**-1.38**	**-1.45**	**-0.35**
	High (all res. – manure)	**0.71**	1.00	**1.11**	**0.79**	s	**56**	**-0.75**	**-1.06**	**-0.19**
						hac	**75**	**-1.01**	**-1.06**	**-0.26**
	High (all res. + manure)	**0.71**	1.00	**1.38**	**0.98**	s	**70**	**-0.07**	**-0.10**	**-0.02**
						hac	**93**	**-0.10**	**-0.10**	**-0.02**
Grass [8]	Nominally, medium/high	1.00	1.00	1.00	1.00	s	71	0	0	0
						hac	95	0	0	0
	Improved, medium	1.00	1.14	1.00	1.14	s	81	0.50	0.70	0.13
						hac	108	0.66	0.70	0.17
	Improved, high	1.00	1.14	1.11	1.27	s	89	0.92	1.33	0.24
						hac	120	1.24	1.33	0.32

[1] FFF = FLU * FMG * FI
[2] Soil Type, both cold temperate and moist. Sandy soil (s) (SOC_{REF} = 71 ton C in 0-30 cm) or soil with high activity clay (hac) minerals (SOC_{REF} = 95 ton C in 0-30 cm). Data SOC_{REF} : IPCC (2006), table 2.3.
[3] SOC-stock, calculated 20 years after land use change has occurred, according to [1]
[4] Yearly change in SOC-stock: [5] as % of SOC_{REF}; [6] as g/kg, layer 0-30 cm, bulk density 1.3 kg/L
[7] Long-term cultivated, full tillage, temperate, moist cropland
[8] Nominally managed (= non–degraded) or improved temperate grassland

IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF) http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html.

Appendix 2 Data used for constructing figure 2

The table below gives the data, grouped by land use, taken from table 2 in Reijneveld et al. (2009), that were used for constructing figure 2.

SOC_{init} was calculated for the middle of the period investigated by Reijneveld et al., from the value measured at the end of the period (2003) and the slope for the whole period. This way of calculation was also used by Bellamy et al. (2005).

	Soil type and region in NL	Soil use	Samples	SOC 2003	Slope b	SOC init. *
1	Marine clay, north	Grass	16849	57	-0.55	64
4	Riverine clay, central	Grass	12660	53	0.37	49
5	Peaty clay, north	Grass	9806	155	-0.98	167
6	Peaty clay, west	Grass	5889	88	-0.27	91
7	Reclaimed peat, north-east	Grass	4583	70	-0.07	71
8	Sand, south	Grass	57594	24	0.18	22
9	Loess, south	Grass	7720	33	0.34	29
1	Marine clay, north	Arable	23830	13	-0.02	13
2	Marine clay, south-west	Arable	56418	12	0.03	12
3	Marine clay, central-west	Arable	4615	21	0.18	19
7	Reclaimed peat, north-east	Arable	40497	63	0.08	62
8	Sand, south	Arable	49344	17	0.01	17
9	Loess, south	Arable	13977	13	0.02	13

* calculated as: $SOC_{init} = SOC_{2003} - 12*(\text{Slope b})$