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Regional characterization of the long-term change in soil organic carbon under intensive agriculture

M. Van Meirvenne, J. Pannier, G. Hofman & G. Louwagie

Abstract. To study the change in soil organic carbon (SOC) since it was recorded during the Belgian National Soil Survey some 40 years ago, we recently revisited 939 locations still under use as arable land. The study area comprised almost the entire province of West Flanders (about 3000 km^2) characterized by profound changes in its arable land management.

Taking the increased ploughing depth (by 9.8 cm on average) into account, a significant ($P = 0.001$) increase of the SOC content by 0.2% on average was found. Expressed as an amount, the SOC in the topsoil rose by 9.3 t/ha on average, representing an increase of 25%. This is comparable with the conversion of arable land into grassland for 2 to 3 decades.

Geostatistical tools were used to map the SOC at the two times of observation. These showed that most of the spatial variation occurred within about 4 km. Since the community level is the smallest spatial resolution on which agricultural statistics are gathered officially, a detailed modelling of the change in SOC was impossible. However, by selecting communities with extreme changes in SOC, we found indications that the major source of increase in SOC was due to the large increase in pig breeding.

Keywords: Carbon, soil organic matter, arable land, intensive farming, Belgium

INTRODUCTION

Modern European agriculture, i.e. monocultures with limited return of crop residues to soil and the use of mineral fertilizers, is generally associated with declining soil organic carbon (SOC) (Allison, 1973). However, the long experimental period (generally in the order of decades) required to observe significant changes in SOC has limited studies on its long term behaviour (Van Der Linden *et al.*, 1987). Correspondingly, the range of conditions that could be studied is also rather limited. Notable examples include Jenkinson & Rayner (1977) and Jenkinson (1991).

In the province of West Flanders, Belgium, the on average 40-year-old data of the National Soil Survey (taken between 1947 and 1962) offer a unique geo-referenced database to study the change in SOC. Based on these data and a recent resampling we studied the long term difference of this variable in arable fields. This province is of special interest since its land use and soil management underwent profound changes in the last decades. Two particular developments are important. First, intensive pig breeding increased nearly eightfold. In 1960, there were 295 000 pigs in this province (N.I.S., 1960). In 1990 the number of pigs had increased to 2 280 000 (N.I.S., 1990). So over this time period the average amount of pig slurry supplied to land increased eightfold. Similar changes took place in the sandy regions of The Netherlands, north Germany, Denmark, west France (Brittany) and north-east Spain (Catalonia). Second, a conversion took place from the conventional arable crop rotation to intensively cultivated field-grown vegetables. Between 1960 and 1990, the ratio of the area of land being used for horticulture to the total area of land under cultivation increased from 0.87% to 6.9% (N.I.S., 1960 and 1990). This conversion influenced both the quantity and the quality of the organic material supplied to soil (Demyttenaere *et al.*, 1989).

The objectives of this paper were threefold: (1) to compare quantitatively SOC at the same locations after a time interval of approximately 40 years; (2) to map on a regional scale the SOC at the two times of observation; and (3) to interpret and explain any observed changes.

This research will allow us also to evaluate the usefulness of SOC measured during the National Soil Survey for characterizing the present-day SOC content. In Belgium, considerable effort is being devoted to the creation of a soil database (Van Orshoven *et al.*, 1988) and its use in a Soil Information System. However, the only available data covering the whole nation were recorded between 45 and 25 years ago. So one could question the usefulness of time dependent variables, such as the SOC, for studies based on these data, especially in areas where important changes in land use and soil management have occurred.

MATERIALS AND METHODS

Study area and data

Our study area covered almost the entire province of West Flanders (3164 km^2). Figure 1 shows a generalized map of the soil texture classes and landscape units of this province based on the map of Marechal & Tavernier, 1974. The units identified were the Polder area (791 km^2), the sandy area (570 km^2) and the sandy loam to silt loam area (1598 km^2). Urban areas, sea dunes and alluvial areas (200 km^2) were excluded.

Within the frame of the National Soil Survey, our department visited more than 2200 locations between 1947

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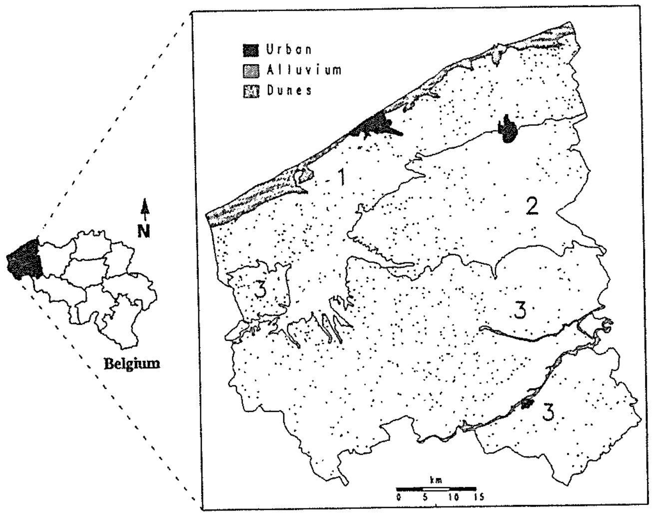

Fig. 1. Left: location of West-Flanders in Belgium. Right: The generalized soil texture regions of West-Flanders (1 = Polder area, 2 = sandy area, 3 = sandy loam to silt loam area) and the 939 paired sampling sites of SOC (points).

and 1962, but most of the observations were made in the early 1950s. Profile pits were dug, and soil horizons were described and sampled in the conventional way. The coordinates were recorded as well as the land use. This large set of data formed the starting point of our research.

To limit the effect of differences in land use we restricted our investigations to those locations that have been arable since the sampling undertaken during the National Soil Survey. This condition reduced the number of sites to 939 with 1952 as the median year of sampling (s = 3.86 year). These SOC data we called 'Survey 1'. Because the 'exact; sampling locations (estimated error on locating a sampling point was 10 m) are known (Fig. 1), we revisited these locations between 1989 and 1994. The depth of the plough layer was observed visually, and soil samples were taken by means of an auger (ϕ 5 cm) at 5 locations within a circle of 4 m radius. At each location samples were bulked and mixed. These mixed samples were analyzed for SOC using exactly the same Walkley & Black procedure as was used during the National Soil Survey (De Leenheer, 1959). These SOC results formed the 'Survey 2' data set. To be able to compare both surveys, we used the present plough layer depth as reference depth (the ploughing depth had generally increased since Survey 1) and calculated a weighted mean value for the SOC content over this depth at each corresponding location of Survey 1. This procedure is illustrated in Table 1. It shows that for this sampling location the percentage of SOC in the plough layer decreased between 1951 and 1990 from 1.41% to 1.39%. However, the depth of ploughing increased from 22 cm to 36 cm. Since the subsoil contained less SOC at the time of Survey 1, the SOC actually increased over the depth of the present plough layer by 0.28% or by 14.0 t/ha. This is an increase of the C-pool in the topsoil of 25%. Calculation of the change in quantity of SOC assumed that soil density was unchanged. It was impractical to measure soil density, but to avoid misinterpretation of soil depth, recently ploughed fields were never sampled.

In this way we obtained 939 paired observations of the SOC for the same location and for the same soil depth, but differing by about 40 years.

Spatial inventory

SOC has recently been mapped for Great Britain by Howard *et al.* (1995). These authors used the soil maps of England and Wales and of Scotland to determine the dominant soil association per 1 by 1 km grid cell, which was the spatial resolution they used for the graphical display of the result. These soil associations were then linked with a soil profile database.

We chose to use geostatistical methods (Webster & Oliver, 1990) to map the SOC content of the topsoil of arable land in our study. Provided that the condition of quasi stationarity can be accepted, these methods have been shown to be suitable for the continuous spatial prediction of soil variables, even for large areas such as ours (McBratney *et al.*, 1982 ; Van Meirvenne *et al.*, 1990). Therefore, variograms were calculated to identify the structure of the spatial variation of the SOC content for both surveys. No anisotropy was detected, so isotropic experimental variograms were used. A theoretical model was fitted using weighted least squares estimation. The validity of the assumptions involved was checked by cross validation. Each value was removed in turn from the set, and the value at that point estimated from the remainder by ordinary point kriging. Several criteria were used, evaluating the presence of bias and whether the kriging errors were consistent with the predicted variances.

Once the kriging conditions were optimized, a map of the SOC content was made by ordinary block kriging to illustrate the continuous spatial behaviour of this variable. Block dimensions of 850 m × 850 m were chosen to represent a good balance between the sampling density and the spatial resolution of the map.

Table 1. Illustration of the calculation of the SOC (% and t/ha) over the same soil depth for the two surveys at one sampling location (nr. 37W13)

	1951 (Survey 1)			1990 (Survey 2)
	Plough layer	Subsoil	Combination of the two layers	
Thickness (m)	0.22	0.14		0.36
Density (t/m^3)	1.42	1.45		1.42
Mass of soil (t/ha)	3124	2030		5112
SOC (%)	1.41	0.64	1.11†	1.39
SOC (t/ha)	44.1	13.0	57.1	71.1

†Average weighted by horizon thickness.

RESULTS AND DISCUSSION

Change in SOC over the observed time period

The descriptive statistics for the SOC contents of both surveys and their difference are summarized in Table 2 and the corresponding histograms are shown in Figures 2 and 3.

The range in SOC for both surveys was similar (0.4–3.2%). However, the mean value increased over the 40 years from 1.07% to 1.27%. The distributions of the original data are positively skewed. But due to the larger mean value, the skewness of the data in Survey 2 is smaller than that of the data in Survey 1. Consequently the coefficient of variation is also smaller (29.1% for Survey 2 and 37.4% for Survey 1). Using average densities of the plough layer as a function of the soil texture classes (Van Hove, 1969), we converted the % SOC to t/ha present in the plough layer (Survey 2 data) or over its equivalent depth (Survey 1 data), as

Table 2. Descriptive statistics of the SOC of the two surveys and their difference, based on 939 observations

	Original data				Ln transformed	
	Survey 1	Survey 2	Difference (Survey 2–Survey 1)		Survey 1	Survey 2
	(%)	(%)	(%)	(t/ha)†	(Ln%)	(Ln%)
Minimum	0.40	0.43	−1.26	−48.96	−0.92	−0.84
Maximum	3.01	3.26	1.55	64.52	1.10	1.18
Mean	1.07	1.27	0.20	9.25	0.01	0.20
Variance	0.159	0.136	0.126	252.2	0.116	0.078
Skewness	1.42	1.19	−0.17	−0.02	0.42	0.14
Kurtosis	2.49	2.61	1.56	0.95	0.05	0.44

†Assuming an unchanged soil density.

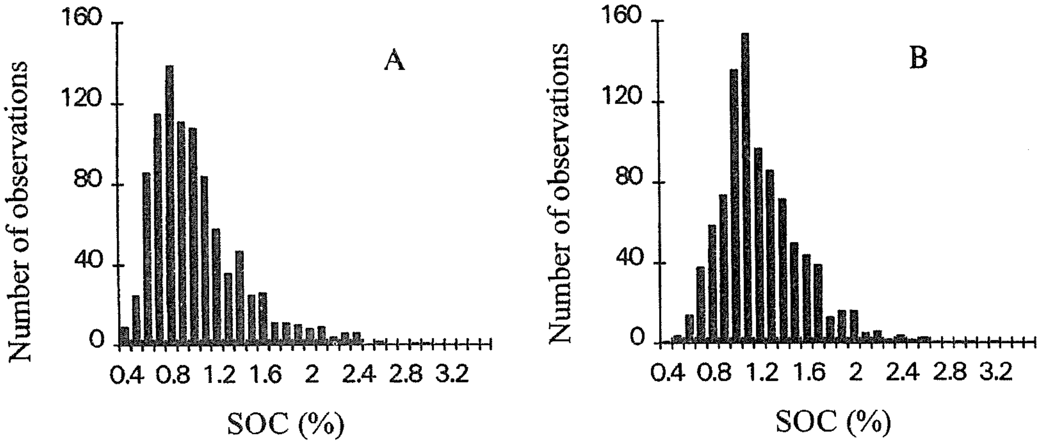

Fig. 2. Histograms of the original SOC data of both surveys (A = Survey 1, B = Survey 2).

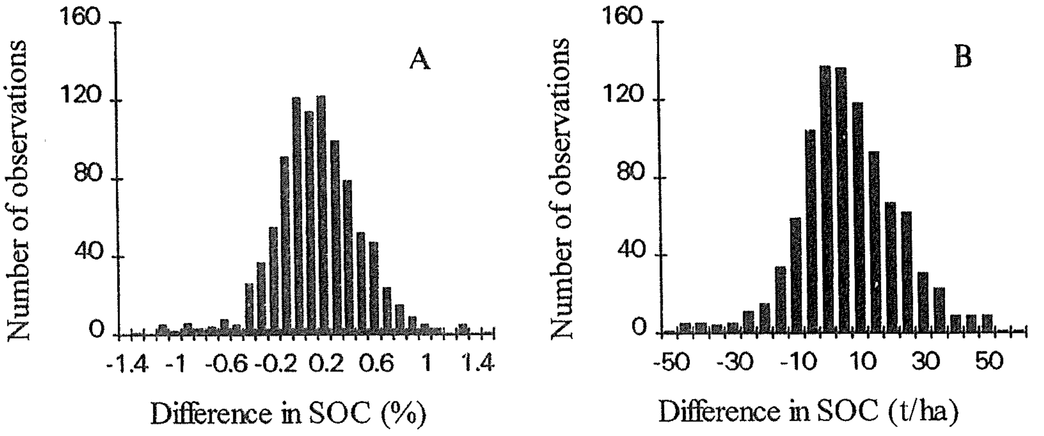

Fig. 3. Histograms of the difference (Survey 2 - Survey 1) in SOC between the two surveys (A = difference in %, B = difference in t/ha, assuming an unchanged density of the soil).

illustrated in Table 1 for one sampling location. The average difference in SOC was 9.3 t/ha, representing an average increase of 25.8%. So it can be concluded that within 40 years the amount of SOC of these arable soils increased by about 25% on average, and in the same time its spatial heterogeneity decreased somewhat.

Both datasets of %SOC were logarithmically transformed (Table 2). After transformation, both the skewness and the kurtosis approached zero. Therefore, both distributions were best represented by a log-normal distribution function.

Table 3 presents the statistics of a paired *t*-test for the entire province and each soil texture region separately. All *t*-values were well in excess of the critical *t*-value at the 0.001 level of probability. So, on a paired samples basis there were highly significant differences between Survey 1 and 2, both for the entire province and within each soil texture region. The increase of SOC was largest in the sandy loam to silt loam region (average increase 0.23%), and smallest in the Polder region (average increase 0.15%).

Over the same period, farmers started to plough deeper. The average depth of the plough layer increased from 22.4 ± 4 cm) observed during Survey 1 to 32.2 ± 5 cm) measured during Survey 2. If this change in land management had not occurred, the SOC of the plough layer expressed as a percentage, would have increased by more than was actually observed.

Table 3. Statistics for a paired *t*-test performed on logarithmically transformed data (mean (%) and standard deviation (%) of SOC were back-transformed to facilitate the interpretation)

Region	No. of samples	Survey 1	Survey 2	*t*†
West Flanders	939	1.07 ± 0.37	1.27 ± 0.36	19.45***
Polders	319	1.23 ± 0.38	1.37 ± 0.37	7.14***
Sandy	132	1.31 ± 0.47	1.49 ± 0.42	6.40***
Sandy loam to silt loam	488	0.90 ± 0.26	1.14 ± 0.28	18.69***

†One-sided paired *t*-test, with $t = 3.09$ for $P = 0.001$***

Variograms

We had access to another dataset of 390 SOC measurements for our study area made in the same way between 1991 and 1994, but without a paired observation made during Survey 1. So for the geostatistical analysis we enlarged the Survey 2 dataset to 1329 observations. For each dataset (Survey 1 and the enlarged Survey 2 data set) experimental variograms were calculated for the whole study area, and for each soil texture region separately (Fig 4). In order to stabilize the spatial variance we used the logarithmically transformed SOC data.

All the experimental variograms were modelled by a double spherical model (McBratney & Webster, 1986):

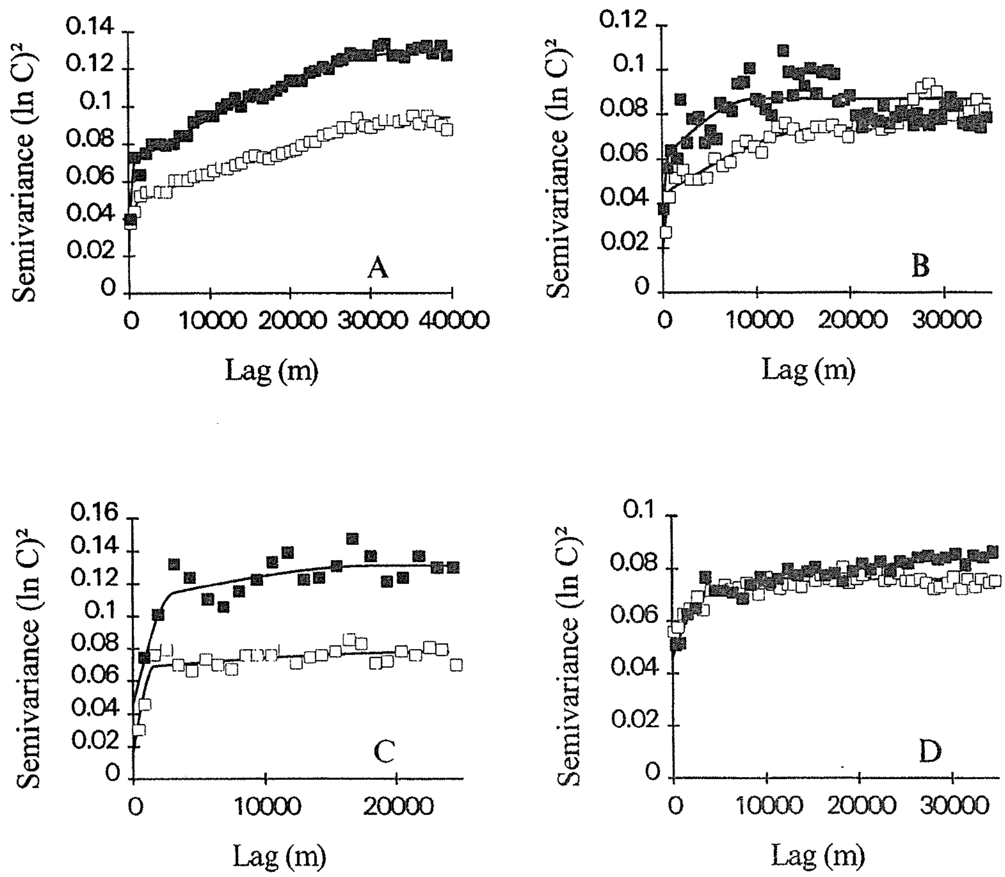

Fig. 4. Experimental variograms (points) and fitted double spherical models (curves) of the entire province (A) and the three textural regions: Polders (B), sandy area (C) and sandy loam to silt loam area (D) for Survey 1 (■) and Survey 2 (□).

$$\gamma(h) = c_0 + \gamma_1(h) + \gamma_2(h)$$

$$\gamma_1(h) = c_1\left[\left(\frac{3h}{2a_1}\right) - \frac{1}{2}\left(\frac{h}{a_1}\right)^3\right], \text{ for } 0 < h \leqslant a_1$$

$$\gamma_1(h) = c_1, \text{ for } h > a_1$$

$$\gamma_2(h) = c_2\left[\left(\frac{3h}{2a_2}\right) - \frac{1}{2}\left(\frac{h}{a_2}\right)^3\right], \text{ for } 0 < h \leqslant a_2$$

$$\gamma_2(h) = c_2, \text{ for } h > a_2$$

and

$$\gamma(0) = 0$$

with $\gamma(h)$ the semivariance for lag distance h, c_0 = the nugget variance, c_1 and c_2 = the sill variances, and a_1 and a_2 the ranges. The fitted model parameters are given in Table 4. The double spherical structure indicates two distinct sources of variation acting at two different scales. The short-range (a_1) component can be interpreted as a farming effect. Its spatial dimension is 1–3 km. The variance increases rapidly with increasing distances in this range. The long-range (a_2) variation can be attributed to regional differences in soil properties and land management, acting at dimensions of the order of 10s of km. The variance increases but less rapidly than the farm scale component. Due to the regional nature of Survey 1 small distance lags (< 100 m) were absent, inducing quite large estimated nugget variances, which ranged between 15.5 and 69.7% of the total sill variance. All variograms of Survey 1 lie above those of Survey 2 when shown on the same axes. The most important difference is found for the sandy region, and the smallest for the sandy loam to silt loam region. However, the sampling support was different for the two surveys. For Survey 1 the support was one profile pit, representing an area of approximately 1 m^2. For Survey 2 we took a pooled sample of 5 samples taken within a radius of 4 m, representing an area of about 50 m^2. To evaluate the difference in sampling support we kept the five individual samples at four locations within the sandy region. These were individually analysed for SOC. The average variance of the log-transformed results was 0.008 (ln %C). This indicates that the regularization effect of our sampling procedure accounted for about 27% of the difference between the nugget variance of the variograms of Survey 1 and 2 for the sandy region. So, the degree of variability decreased over the 40 years, probably due to a homogenization in agricultural land use and management, despite the increase of the mean SOC. Since the shapes of the variograms remain similar for the two surveys, the pattern of spatial variation of SOC remained similar.

For the three soil texture regions we can conclude that the major part of the spatial variation occurs within a range of less than approximately 4 km. Since the variograms of the different regions differ considerably from the one of the unstratified data set, we proceeded with stratified kriging.

Table 4. Parameters of the double spherical model fitted to the experimental variograms

Region	c_0 (Ln %C)^2	c_1 (Ln %C)^2	a_1 (m)	c_2 (Ln %C)^2	a_2 (m)
Survey 1					
West Flanders	0.020	0.049	800	0.060	35950
Polders	0.024	0.036	700	0.027	10100
Sandy	0.046	0.063	3000	0.022	18900
Sandy loam to silt loam	0.045	0.024	3700	0.015	36000
Survey 2					
West Flanders	0.031	0.017	1300	0.046	41300
Polders	0.017	0.027	1000	0.030	17500
Sandy	0.017	0.051	1600	0.010	23200
Sandy loam to silt loam	0.053	0.015	4300	0.008	19300

Block kriging of the SOC content

The logarithmically transformed data were block-kriged and back-transformed to original values. The results are shown in Figures 5 and 6 assuming all the land is arable. The associated kriging standard error was approximately 20%. For both surveys, the largest SOC contents were in the Polder area and the sandy region, as concluded before. For the Polders this can be explained by the presence of a stable clay-humus complex, decreasing the mineralization rate. The sandy area had traditionally a land management oriented to large organic matter applications to improve its water and nutrient holding capacity. By comparing the two maps, regional differences in the change of SOC can be observed. Within the sandy loam to silt loam area, SOC increased almost everywhere. However, the Polders and the sandy region show areas with an accumulation of SOC and others with a constant or even decreasing SOC level.

Modelling the change of SOC

The finest spatial resolution for which comprehensive information concerning land use and livestock is gathered officially is the community. The variograms showed that most of the spatial variation occurs within a rather small range of about 4 km. However, the mean area of a community in West Flanders is approximately 47 km^2. This means that the range of spatial variability of SOC is largely absorbed within the scale of a community. Therefore we must conclude that the spatial resolution of information from agricultural statistics is too coarse to offer any possibility for modelling and simulating the detailed change in SOC content.

SOC and intensive agriculture at a community scale

In order to elucidate the most important sources causing the change in SOC, we selected two communities within the sandy area with contrasting changes in SOC. The first community, Zedelgem, was characterized by almost no difference in SOC between the two surveys (difference of 0.04% between the average SOCs of the two surveys, Table 5). The second community, Torhout, showed an above average increase in SOC content of the arable land (difference of 0.34% in SOC). Table 5 also gives some agricultural statistics of both communities, recorded in 1960 and 1990. During this time the area of arable land decreased slightly, but the change in land use was considerable. In both communities there was a decrease in the area under cereals and an increase in the number of pigs and cattle. But Zedelgem was characterized by a smaller change in these enterprises

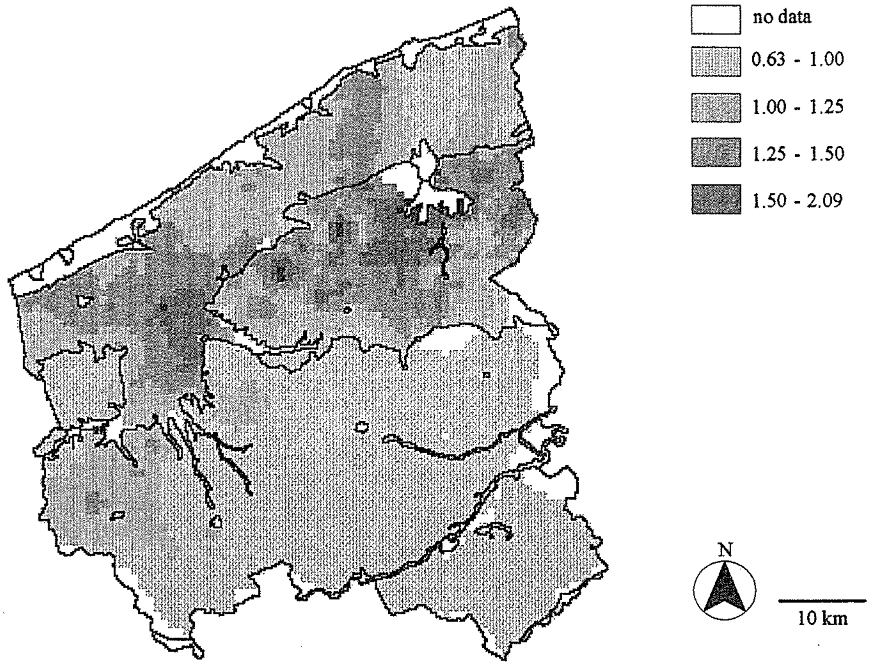

Fig. 5. Block kriged SOC content (%) for Survey 1 (1947-1962).

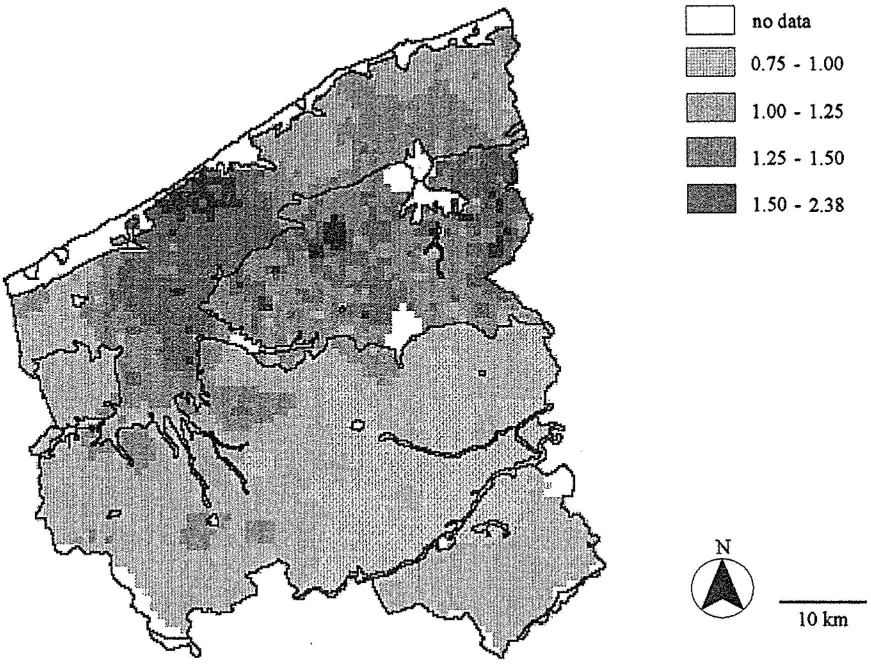

Fig. 6 Block kriged SOC content (%) for Survey 2 (1989-1994).

than Torhout. The area under cereals decreased to about one third in Zedelgem, but to about one fifth in Torhout. Over the same period, the number of pigs increased six times in Zedelgem and more than eleven times in Torhout.

Based on the yearly agricultural statistics for these two communities, we calculated the effective organic carbon (EOC) formed as a function of the type of organic material applied. The EOC is defined as the remains of organic material still present in a soil one year after the application (Consulentschap voor Bodemaangelegenheden in de Landbouw, 1980). This EOC is equivalent to the humification coefficient defined by Henin *et al.* (1960) and Hofman & Van Ruymbeke (1980). We assumed that all organic matter produced in a community was supplied equally to all arable land inside this community. Table 6 contains the conversion factors that were used to calculate the EOC from the amounts of annually produced organic material. For pig manure a production of 1.59 t/year/animal was used, for cattle 11.2 t/year/animal (De Batselier, 1993). According to

Table 5. Change in SOC and some agricultural statistics of the two communities Zedelgem and Torhout, both located in the sandy area

	Zedelgem	Torhout
Area (km^2)	61.2	43.1
SOC		
No. of samples	16	15
SOC (%) Survey 1 (m ± s)	1.56 ± 0.46	1.20 ± 0.51
SOC (%) Survey 2 (m ± s)	1.60 ± 0.37	1.54 ± 0.39
Agricultural statistics - 1960		
Area arable land (ha)	3994	3045
Area cereals (ha)	1559	1142
No. of pigs	10349	9041
No. of cattle	8770	6184
Agricultural statistics - 1990		
Area arable land (ha)	3504	2600
Area cereals (ha)	598	249
No. of pigs	62097	103663
No. of cattle	14492	9922

Table 6. Cultivated crop and amount of EOC produced (Titulaer & Hoekstra, 1986)

Cultivated crop	EOC produced (kg/ha)
Vegetables	350
Potatoes	440
Green fodder (maize, beet,...)	500
Industrial crops (sugarbeet, flax,...)	600
Cereals (except straw)	800

EOC = effective organic carbon.

Preuter (1986), the EOC produced per tonne of animal slurry is 16 kg for pigs and 15 kg for cattle.

The result (Fig. 7) shows that in both communities the EOC produced in 1960 amounted to about 1100 kg/ha of arable land. In 1990 this production rose to about 1800 kg/ha in Zedelgem and to 2200 kg/ha in Torhout. In both communities, pig slurry was responsible for the major

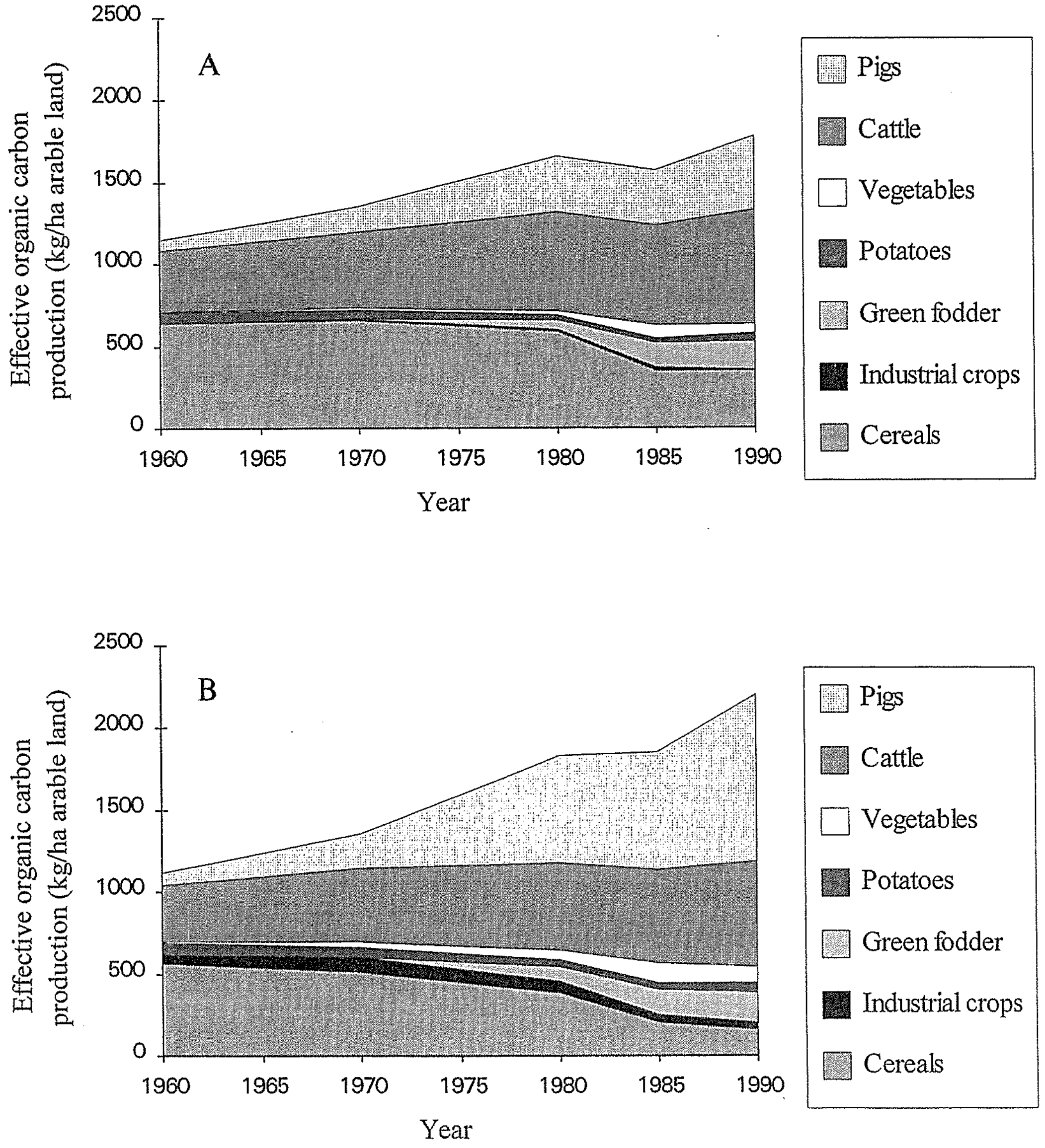

Fig. 7. Change in effective organic carbon production calculated from the agricultural statistics for Zedelgem (A) and Torhout (B) between 1960 and 1990 (the sequence in the Figures is the same as in the legend).

part of this increase. This source of organic matter represents the major cause of the difference in change of SOC between the two communities. Similar calculations were made for the other two textural regions, and the results were similar (Louwagie, 1995). Therefore, we concluded that the major reason for the change in SOC was the dramatic change in land management due to a very large increase in pig numbers.

CONCLUSIONS

On arable fields we found that, within the same soil depth, the SOC content has significantly ($P = 0.001$) increased by 0.2% on average over the last four decades. However, this difference is complemented with an increased ploughing depth of 9.8 cm on average. This reduced the increase in SOC expressed as a percentage, since the subsoil contained less SOC at the time of Survey 1. Expressed as an amount, the SOC rose by an average of 9.3 t/ha, considering the same soil depth. This represents a 25% increase of the C-pool of the topsoil. Reporting on some of the long term experiments at Rothamsted Experimental Station, Johnston (1973) found that all arable rotations lost organic matter. A field originally in old permanent grass lost 25% of its SOC (which was originally 2.75%) after 15 years of arable rotations with a marked fall in the rate of loss in the last few years. In an old arable field at Woburn with originally 1% SOC, he found that the SOC content was stabilized under arable-with-roots by adding 38 t/ha farmyard manure (FYM) every 5 years. When this field was put into continuous grazed ley for 28 years, the SOC increased by 28% without FYM and by 35% with the FYM treatment. These results suggest that the average increase of SOC we found is of the same magnitude as that expected from the conversion of an arable field into grassland for 2 to 3 decades. This illustrates the profound change in land use and soil management that the arable fields of the West Flanders province underwent during the last 40 years.

The increase in SOC we found, will improve many soil properties, for example water and nutrient holding capacities. The nitrogen supply from mineralization of the SOC will also be greater. Although this increase will have increased soil fertility, it may also cause extra nitrate leaching unless fertilizer N application is adjusted to take account of the enhanced soil supply. We strongly advise that the N mineralization capacity of soil is included in all fertilizer N advice (Hofman, 1988).

Geostatistical tools were used to map the SOC at the two dates of observation, with variograms modelled by nested structures. These variograms showed that the largest part of the spatial variance of the SOC of both surveys occurred within a spatial dimension of about 4 km. Therefore, the agricultural statistics gathered at community scale were spatially too coarse to model and simulate the change of SOC in detail. By selecting communities with clear differences in their average change in SOC, and by converting the organic matter produced into EOC present in the soil, we obtained a clear indication that the major source of increase in SOC was due to the intensified pig breeding.

This research also indicates the need to revise the soil database of the National Soil Survey, especially in those areas where land use and soil management have undergone major changes over the time period involved.

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