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Influence of estimation procedure on soil organic carbon stock assessment in Flanders, Belgium

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Abstract. The purpose of the study was to determine the soil organic carbon (SOC) stock for Flanders, Belgium and to evaluate various methods for assessing SOC stock. The assessment methods first determined the SOC density (C mass per unit area) for pedons in a database of soil properties, and then spatially distributed the SOC density to soil and soil/land use categories on a map. The results showed that the pedon SOC density is influenced by drainage class, texture and land use/land cover. The SOC density estimation method significantly influences results and leads to differences of up to 6% in total estimated SOC stock for Flanders. Use of various spatial distributing methods creates differences of up to 2% in total estimated SOC stock. The largest difference in SOC stock estimate between any combination of assessment methods was 7% (125.6 Tg vs 134.9 Tg). These findings emphasize the importance of complete spatial soil databases of high quality that reduce uncertainty of estimates for use in research examining the role of soils in the C cycle. The results indicate that the need for these databases is greater than the need to standardize methods to determine the spatial distribution of SOC. A map of the distribution of SOC density shows that in Flanders a large proportion of SOC is stored in sandy soils in the north of the territory.

Keywords: Organic carbon, soil carbon, bulk density, GIS, Belgium

INTRODUCTION

It is generally recognized that the pedosphere contains more organic carbon than the atmosphere and biosphere combined (Post *et al.* 1990). Consequently, soil organic carbon (SOC) is an important component of the C cycle and must be considered for evaluating the flux of greenhouse gases between the terrestrial spheres and the atmosphere. Global SOC pools are difficult to estimate because of incomplete knowledge of specific soil properties at a global scale (Batjes 1996), the high spatial variability of SOC (Bird *et al.* 2002), and the different effects of the factors controlling SOC (Cote *et al.* 2000). Thus, regional and national scale studies of SOC are necessary to refine global estimates (Bernoux 2002). For these studies spatial databases of soil properties and environmental driving variables are needed (Kern 1994; Batjes 2000).

Although global (Bolin 1970; Bohn 1982) and regional (Parton *et al.* 1987; Huntington *et al.* 1988) SOC estimates had been made earlier, the first national estimates were made less than a decade ago (Kern 1994; Howard *et al.* 1995; Schroeder & Winjum 1995). Kern (1994) compared three methods to spatially distribute point SOC data for the contiguous USA. Results showed that the methods produced similar national SOC totals, but using an ecosystems complex map as the spatial reference did not yield spatial patterns that were as reliable as those produced from a map of major land resources and a soil map of the world. A national scale soil map was not used by Kern but a method to employ such a map as the spatial reference to make a SOC inventory for the USA was introduced by Bliss *et al.* (1995). In this method, SOC values are calculated at soil series level from data in the soil interpretations record (SIR) database, and then are assigned to the corresponding map unit.

Howard *et al.* (1995) mapped the geographical distribution of SOC in Great Britain in 10 km × 10 km blocks. Their estimates were based on the dominant soil series and land cover type for 1 km × 1 km blocks, the bulk density for the soil series and the SOC content for each soil series/land cover combination from representative soil core data. Except for Scottish peat, SOC was estimated to 1 m depth. The total SOC stock for Great Britain was estimated at 22 Pg. An estimate of only 10 Pg SOC for British soils resulted from adjusting the estimate for the bulk density of peat from $0.35\,\mathrm{g\,cm^{-3}}$ to $0.11\,\mathrm{g\,cm^{-3}}$ and changing estimation procedures for land cover type classification and distribution (Milne & Brown 1997). An approach similar to that used by Milne & Brown (1997), but with some modifications to take account of differences in available data sources, was employed in Northern Ireland (Cruickshank *et al.* 1998). Carbon densities for mineral soils are low (10–$40\,\mathrm{kg\,m^{-2}}$) in Northern Ireland and generally coincide with spatial patterns in vegetation C density (Cruickshank *et al.* 1998).

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To estimate the SOC stock for Brazil, an ecosystems approach using a remotely sensed image to classify and map ecosystems was developed initially (Schroeder & Winjum 1995). The SOC density for the 0–1 m of the soil in the various ecosystems was obtained from a global database (Zinke *et al.* 1983). Later, a map of soil–vegetation associations (SVAs) was made to estimate SOC stocks to a depth of 30 cm (Bernoux *et al.* 2002). To delineate the SVAs, a soil map was reclassified into 6 general soil types and intersected with a generalized vegetation map. For each of the 75 resulting SVAs the SOC density was calculated as the median of the C density of soil profiles in the corresponding SVA. The SOC density calculations included bulk density estimation with pedotransfer functions (PTFs) from a study of Amazon soils (Bernoux *et al.* 1998b). Results show that about half of Brazil's SOC pool is stored in the top 30 cm (Bernoux *et al.* 2002).

For France, an estimate of SOC to a depth of 30 cm was made using a combination of geo-referenced soil and land use databases (Arrouays *et al.* 2001). Mean values for soil bulk density were calculated per land use from bulk density and coarse fragment data available for some of the soil profiles in the database. Subsequently, C densities were determined by soil/land use category as a product of mean bulk density, SOC content and horizon thickness for profiles in the corresponding category. The total C stock for the upper 30 cm of soil in France was estimated at 3.1 Pg (Arrouays *et al.* 2001).

A national or regional SOC stock estimate for Belgium has not been published, although some related work has been carried out. A local SOC stock estimate in two types of deciduous forest revealed little difference in total C stock between the forests, but the C distribution over the different ecosystem components was related to botanical and soil characteristics (Vande Walle *et al.* 2001). In a pine tree stand on sandy soil, 47% of total C was found to be in the soil (Janssens *et al.* 1999). A study of SOC in arable land in one province (3000 km^2) showed that SOC significantly increased between 1950 and 1990 (Van Meirvenne *et al.* 1996). The main source for the increase was a large expansion in pig breeding.

Bulk density (BD) is one of the parameters needed to determine SOC density for pedons but is often missing in national and regional databases and, consequently, has to be estimated (Bockheim *et al.* 1999; Bernoux *et al.* 2002). Bulk density estimation errors can potentially have a large influence on calculated SOC densities (Milne & Brown 1997). Many studies have developed and evaluated statistical models that relate BD to soil characteristics that are more readily available in soil databases. In these studies it has been shown that SOC, sometimes in combination with clay content, is the single most important factor in estimating BD (Manrique & Jones 1991; Bernoux *et al.* 1998a), but texture can also be highly correlated with BD (Van Hove 1969). Boucneau *et al.* (1998) evaluated the applicability of various models to estimate BD in northern Belgium. They concluded that the Manrique & Jones (1991) models based on individual USDA soil orders performed the best overall. In the present study BD was estimated with the general model of Manrique & Jones (1991), with the Manrique & Jones (1991) models based on individual USDA soil orders, and with the Van Hove (1969) approach.

The purpose of the present study was to estimate the SOC stock for Flanders, one of the three federal regions of Belgium, to evaluate alternative SOC stock estimation procedures, and to describe the spatial distribution of SOC in Flanders. Previous studies examining multiple SOC estimation approaches and comparing various soil databases, digital soil maps and soil-type aggregation methods have demonstrated that results can differ significantly (Kern 1994; Homann *et al.* 1998; Batjes 2000). We employed one pedon database and one digital soil map but have compared methods to estimate SOC density for the pedons in the database and spatial distributing approaches to assign the pedon SOC density to map units.

METHODS

Data

The soil survey of Belgium was carried out between 1947 and 1974 at a scale of 1 : 5000. The legend for the survey was at the level of soil series, which are based on a geomorphologic classification system in the polders near the coast, and a morphogenetic classification system using substrate, texture class, drainage class and profile development in the rest of the country. In the 1990s the hardcopy maps for Flanders were digitized in a series of consecutive and coordinated procedures (Ondersteunend Centrum 2001).

The soil profile data for north of the rivers Maas and Samber, including Flanders, were converted to digital format in various steps (De Leenheer *et al.* 1968; Van Orshoven & Vandenbroucke 1993). The resulting database is called Aardewerk-Noord and forms the basis for the present study. In total, 8990 profiles and 48 471 horizons are included in Aardewerk-Noord. About 2000 profile descriptions of the original soil survey were not included in the database because of the poor physical condition of the original data (Van Orshoven & Vandenbroucke 1993). The database was edited by us to make it consistent and complete, and to delete unusable pedons. When the organic carbon (OC) content was lacking for a horizon, the mean of the OC content of the over- and underlying horizons was assigned to the horizon. When the OC data were missing for the topmost or bottommost horizon, or when they were missing for more than one adjacent horizon, the pedon was deleted. Pedons located in Flanders were extracted from the database in a geographical information system (GIS). The resulting database of pedons will be called Aardewerk in the remainder of this text.

The digital land use/land cover (lu/lc) map for Flanders was derived from Landsat Thematic Mapper images from 1995 (Ondersteunend Centrum 1996). The spatial resolution of the images was reduced from the original 30 m to 20 m, with a RMS error of less than 0.5 pixel. The images were subsequently classified with a maximum likelihood classifier into 16 lu/lc categories. These categories were refined with CORINE land cover data (CCE 1993), external road and waterways information, and a digital soil association map, resulting in 27 lu/lc categories.

SOC density

The SOC density (kg m^{-2}) of the pedons was calculated for each horizon by multiplying the BD, OC content, coarse fragment conversion factor, and thickness, and by summing the resulting horizon SOC densities per pedon. The OC content of the horizons in Aardewerk was measured by wet combustion (Walkley & Black 1934) and the coarse fragment content by dry sieving. The BD of the horizons was not included in Aardewerk but was estimated by three methods: (i) general model 1A for all soils of Manrique & Jones (1991); (ii) Manrique & Jones (1991) models 1A, 4 and 5 based on individual USDA soil orders; and (iii) the Van Hove approach (1969). Model 1A of Manrique & Jones uses the square root of the OC content as the sole independent variable, while models 4 and 5 use OC content and texture. For the USDA soil-order based method, model 1A was employed for Inceptisols and Spodosols and models 4 and 5 were used for Alfisols and Entisols, respectively, because they performed better than model 1A for these orders in the original Manrique & Jones study. All three methods (general model 1A for all soils, soil order specific models, Van Hove approach) were modified for the O horizons because for horizons rich in OC the Manrique & Jones models result in unrealistically low BD values, while the Van Hove approach results in seemingly high BD values. For these O horizons, the horizon-specific model 1A of Manrique & Jones (1991) was used when the OC was $\leqslant 12\%$, and the forest floor model of Grigal *et al.* (1989) was used when the OC content was >12%. These two models were used in combination because the horizon-specific Manrique & Jones model still results in very low BD values when the OC content is high, and even in negative BD values when OC >28%, while the Grigal *et al.* (1989) model gives unrealistically high BD values when the OC is relatively low (e.g. 1.7 g cm^{-3} when OC = 3%). The Grigal *et al.* forest floor model performs poorly for horizons with low OC content because it was developed from samples with loss-on-ignition >10%. The point at which both regression models intersect is 12%. Peat horizons were given a BD of 0.3 g cm^{-3} based on Howard *et al.* (1995). Because BD was estimated by three different methods the SOC density was calculated three times for each pedon.

To estimate BD with the order-specific model of Manrique & Jones the Aardewerk pedons had to be allocated to a USDA soil order. Systematically converting Belgian soil series to USDA soil orders is not possible as the two classification systems are based on different principles. Manually assigning Belgian soil series, or individual pedons, to a USDA soil order is somewhat simplified by the fact that only five soil orders occur in Belgium: Entisols, Inceptisols, Spodosols, Alfisols and Histosols. Consequently, it has been possible for soil surveyors to include USDA equivalents for some of the Belgian soil series in the explanatory texts of the Belgian soil maps. This information was used to automatically assign some of the pedons in Aardewerk to a USDA soil order. Pedons of series that could not be converted automatically were examined for key horizons and horizon sequences and allocated to a soil order (Ameryckx *et al.* 1995). Some series could not be converted because the soil map explanatory texts described them only briefly and their individual pedons in Aardewerk lacked classifiable profile characteristics. Consequently, 324 pedons could not be assigned to a USDA soil order.

To determine the SOC stock, pedon SOC densities were spatially distributed and assigned to polygons on the digital soil map of Flanders in three ways. In the first method a soil map polygon received the SOC density of the geographically nearest pedon that belonged to the same generalized soil type. In the second method the mean pedon SOC density was calculated per soil type per natural region and assigned to all polygons of that soil type in the corresponding region. The natural region of the soil polygons was one of the variables in a secondary attribute table of the digital soil map. For the third method the soil map and lu/lc map were combined in a GIS to create a map of soil type – lu/lc categories. Because the lu/lc variable of the pedons in Aardewerk and the lu/lc map had different categories, they were reclassified into six common lu/lc categories: broadleaf forest, needle-leaf forest, mixed forest, pastures (permanent grass), cropland, and other (mainly built up and infrastructure, some water and heather). The soil type–lu/lc category of the pedons in Aardewerk was obtained by concatenating two existing variables in the database. The mean pedon SOC density was then calculated per soil type–lu/lc category and assigned to all soil map polygons of that category. In all three spatial distributing methods the SOC density for the soil polygons was multiplied by the polygon area and summed for the territory to calculate the total SOC stock in Flanders. To visualize the spatial distribution of SOC in Flanders, the map obtained with the order-specific BD estimation method of Manrique & Jones and the spatial distribution method based on the nearest pedon was rasterized using 0.5 km cells.

RESULTS AND DISCUSSION

Data and methods

After editing the database and extracting pedons located in Flanders, 6314 pedons and 34 846 horizons remained in Aardewerk. The average map density is 1 pedon per 2.2 km^2. The map of generalized soil types consists of 131 152 polygons. The average size of polygon is 0.12 km^2. The humid sand generalized soil type has the largest extent (2500 km^2). The map provides greater geographical detail, and hence leads to spatially more specific results, than maps used in some other national and regional SOC stock estimations (Howard *et al.* 1995; Cruickshank *et al.* 1998; Arrouays *et al.* 2001).

The SOC densities were calculated for the thickness of the pedon as given in the Aardewerk database. In principle, soils in Belgium were surveyed to a depth of 1.25 m but occasionally the depth was less or more, depending on the thickness of the profile and site characteristics. The total SOC stocks calculated in this study, therefore, represent the stock for the whole soil in Flanders, regardless of its thickness. The mean thickness of the pedons in Aardewerk is 1.44 m, the minimum recorded depth is 0.24 m and the maximum 4.93 m. The highest SOC densities are associated with pedon thicknesses in the range of 1.50–1.75 m but there

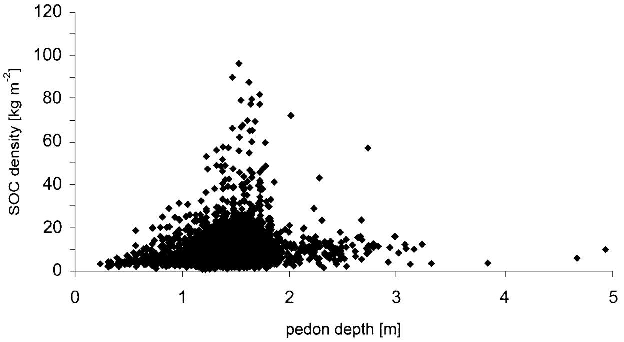

Figure 1. Pedon SOC density vs depth of pedon. Pedon SOC density based on bulk density estimate with order-specific model of Manrique & Jones (1991).

is not a systematic relationship between SOC density and pedon thickness (correlation coefficient is –0.1) (Figure 1).

General results

The OC content of the horizons ranges from 0.0 to 34.6%, the median is 0.3% and the mode 0.1% (Table 1). The coefficient of variation (CV) is 190%. This relatively high CV is mainly due to the high OC contents of some of the O and peat horizons and is not unusual for national scale studies (Arrouays *et al.* 2001). The mean OC content for the various types of horizon is as expected: high for A horizons, low for B and C horizons, except for the Bh horizon which has a high OC content, and high in gley horizons and peat (Table 1).

The mean BDs of the horizons based on the general and order-based model of Manrique & Jones are 1.48 g cm^{-3} and 1.51 g cm^{-3}, respectively, a difference of 2% ($P = 0.02$) (Table 1). The largest difference, 7.5%, is observed for AB and E horizons. The mean BD based on the Van Hove approach is smaller than the BDs based on the Manrique & Jones methods, being 6% and 8% less than the general and order-based models, respectively ($P = 0.02$ and 0.03, respectively). This decrease is largest for horizons with little OC such as the B, Bt, C, 2B/2C and 2B/2Ctrans horizons. Horizons with relatively high amounts of OC (i.e. the A, Ap, Bh and Bg/Cg horizons) have greater BDs with the Van Hove approach. The reason for these specific differences is that in the methods of Manrique & Jones BD is inversely proportional to OC content while the Van Hove approach is exclusively based on texture.

The SOC density for the pedons, based on the order-specific model of Manrique & Jones, ranges from 0.6 kg m^{-2} to 96.4 kg m^{-2}. The mean density is 9.1 kg m^{-2} and the CV is 76%. This mean is comparable to the mean for France, a neighbouring country to Belgium (Arrouays *et al.* 2001). The range of densities and the CV in France were somewhat larger, probably due to the greater variety of soils and natural environments.

In the absence of chemical reduction, SOC density is not related to the drainage class of the pedons (drainage classes a, b, c, d and h; Table 2). Only when gleying reaches the surface (drainage class i) is there an apparent increase in SOC density. This increase may be spurious because of the small number of pedons and the relatively high mean pedon depth for drainage class i. On the other hand, it is well known that seasonal water tables at or near the surface favour the accumulation of organic matter in surface horizons (Batjes & Bridges 1992). When reduction is present (drainage classes e, f and g) the SOC density is considerably higher and increases as depth to gleying and reduction decrease (Table 2).

Table 1. Bulk density (g cm^{-3}) per horizon for three bulk density (BD) estimation procedures.

Horizon	OC (%)	BD M+J all soils	BD M+J order-specific	BD Van Hove	n[d] M+J order-specific
O	8.17	0.84	0.84	0.84	52
A	2.85	1.21	1.21	1.37	1371
Ap	1.21	1.38	1.40	1.41	5655
AB	0.37	1.48	1.59	1.43	767
AC	0.78	1.40	1.41	1.37	2073
Etrans[a]	0.88	1.41	1.43	1.40	169
E	0.47	1.46	1.57	1.41	1557
B	0.18	1.56	1.65	1.41	262
Btrans[a]	0.27	1.52	1.44	1.42	341
Bh	1.30	1.33	1.38	1.39	692
Bs	0.59	1.43	1.53	1.38	1048
Bw	0.49	1.46	1.47	1.40	273
Bt	0.22	1.52	1.59	1.43	1739
BC	0.19	1.54	1.62	1.41	1411
C	0.25	1.54	1.55	1.38	8239
2B/2C[b]	0.26	1.56	1.54	1.37	7174
2B/2Ctrans[a,b]	0.19	1.55	1.58	1.41	513
Bg/Cg	1.29	1.39	1.36	1.39	107
V[c]	13.49	0.30	0.30	0.30	65
Mean/total	0.64	1.48	1.51	1.39	33521

[a] Transitional horizon dominated by characteristics of designated horizon. [b] Horizon below lithological discontinuity. [c] Peat. [d] Total for n is different from total number of horizons after database editing mentioned in text because USDA soil order could not be established for all pedons.
M+J = Manrique & Jones (1991).

Table 2. Mean SOC density (kg m^{-2}) and mean pedon depth (m) per drainage class.

Drainage class[a]	SOC density[b]	Depth	n
a	8.25	1.74	72
b	7.43	1.49	1170
c	7.52	1.43	1091
d	8.10	1.41	2158
h	8.01	1.41	575
i	13.16	1.63	7
e	13.51	1.43	603
f	19.54	1.45	255
g	29.71	1.37	59
Mean/total	9.11	1.44	5990

[a] a, b, c, d, h, i: no chemical reduction present, decreasing depth to gleying; e, f, g: chemical reduction present, decreasing depth to reduction and gleying. [b] Based on bulk density estimate with order-specific model of Manrique & Jones (1991).

In humid and wet locations, pedons with clay and heavy clay texture have higher SOC densities than other textures (Table 3). This influence of texture in general, and of clay content specifically, on stabilizing organic matter is well recognized and has been described for a variety of environments (Parton *et al.* 1987; Burke *et al.* 1989; Cote *et al.* 2000).

Table 3. Mean SOC density (kg m^{-2}) and mean pedon depth (m) for selected generalized soil types.

Soil type	SOC density[a]	Depth	*n*
Dry clay	4.90	1.51	4
Dry sand	7.08	1.53	341
Dry sandy silt	6.16	1.45	240
Dry silt	7.30	1.44	534
Humid clay	10.73	1.49	54
Humid heavy clay	16.28	1.52	42
Humid sand	8.68	1.48	1139
Humid sandy silt	6.48	1.37	1078
Humid silt	7.11	1.26	241
Wet clay	15.57	1.41	211
Wet heavy clay	15.58	1.33	61
Wet sand	12.52	1.51	240
Wet sandy silt	10.32	1.41	427
Wet silt	16.02	1.50	86
Coastal dune	8.42	0.67	26
Inland dune	7.84	1.68	54
Marl soil	21.42	1.48	13
Peaty soil	44.89	1.47	16

[a] Based on bulk density estimate with order-specific model of Manrique & Jones (1991).

Table 4. Mean SOC density (kg m^{-2}) and mean pedon depth (m) per land use/land cover category.

Land use/land cover	SOC density[a]	Depth	*n*
Broadleaf forest	10.82	1.50	233
Coniferous forest	8.53	1.61	247
Mixed forest	9.56	1.61	56
Pasture	12.92	1.43	1536
Cropland	7.35	1.41	3640
Other	10.03	155.00	278

[a] Based on bulk density estimate with order-specific model of Manrique & Jones (1991).

The SOC density of the pedons is dependent on lu/lc (Table 4). Pastures have the highest SOC density, croplands have the lowest SOC density and forests have intermediate densities. This influence of lu/lc cannot be attributed to differences in pedon depth because the two lu/lc categories which contrast in SOC densities (pasture and cropland) have very similar mean pedon depths, while categories with intermediate SOC densities have greater pedon depths that are typically associated with high SOC densities (Figure 1). The influence of crops and grassland on SOC found in the present study is consistent with other studies (Jenkinson 1990; Kern 1994). Grassland soils that are converted to cropland lose 20–50% of their organic matter in 40 to 50 years (Swift 2001). There are some indications that in Flanders SOC under cropland may have increased locally since the original Belgian soil survey (Van Meirvenne *et al.* 1996).

Comparison of SOC stock estimates

Estimates of total SOC stock in Flanders range from 125.6 Tg to 134.9 Tg depending on the estimation procedure (Table 5). The Van Hove approach to estimate BD results in the highest SOC stock estimates, irrespective of the method used to assign pedon SOC densities to soil map polygons. Results obtained with the Van Hove approach are 4.4–5.9% higher ($P < 0.01$) than those obtained with the other BD estimation methods. The BD estimation method based on the general model of Manrique & Jones for all soils consistently gives the lowest SOC stock estimates, although the results are only slightly less than those from the soil-order specific BD model of Manrique & Jones (0.4–0.7% difference). Stock estimates obtained with the Van Hove approach are highest, even though mean BD estimates obtained with this approach are lowest. The reason for this apparent contradiction is that, as explained above, the Van Hove approach results in high BD estimates for horizons rich in SOC, which proportionally contribute most to the SOC density of the pedons. These findings illustrate the importance of robust BD estimation procedures for SOC stock determination.

The method of spatially distributing SOC density based on soil type–lu/lc categories yields stock estimates that are lower than those of the other two SOC density distribution methods (Table 5). Differences range from 0.2 to 2.1% depending on the BD estimation method. The distribution method based on mean SOC densities per soil type and region consistently results in the highest SOC stock estimates. Results of this method are between 1.0 and 2.1% higher than those of the other two methods. These results show that although the distributing method influences SOC stock estimates in the current study (up to 2.1%), BD estimation procedures affect the outcome more (up to 5.9%). The largest difference between any two methods is 7.2% (133.2 Tg vs 125.6 Tg). This difference is somewhat smaller than the maximum variation in stock estimates resulting from the analysis of various databases for the USA (8.0%, Kern 1994) and for South America (8.9%, Batjes 2000). A possible explanation for the smaller variation in Flanders is the smaller diversity of soils. The smaller variation in Flanders may also indicate that variation due to the use of various methods is smaller than that introduced by the use of various databases. This contention, if correct, emphasizes the importance of complete and accurate data for SOC stock estimation.

The differences between SOC estimation methods also have to be examined in the light of errors in the estimation of SOC stocks. Although it is difficult to accurately quantify the error in this type of study (Houghton *et al.* 1999), magnitude and propagation of errors have been discussed in some detail (Homann *et al.* 1998; Bernoux *et al.* 2002). In a study of SOC stock change over time errors were estimated to be as high as 50% (Eve *et al.* 2002), but the Intergovernmental Panel on Climate Change (IPCC) recognizes that the uncertainty on absolute stock values is larger than the uncertainty in changes in SOC stock with time (IPCC 2000). A standard error of 25% was calculated for the SOC stock in Great Britain, based on assumed uncertainties in areal extent of the soils and SOC densities (Milne & Brown 1997). The uncertainty in the SOC stock of Scottish peats was 45%, due to a high uncertainty in the BD and variation in depth of these peats, while the uncertainty for other British soils was 24%. A standard error of 9.4%, which is relatively low for this type of study, was established for the SOC stock in Brazil (Bernoux *et al.* 2002). Assuming that these general error estimates apply to the current study, results demonstrate that differences between the outcomes of various SOC estimation methods are well within the margin of error of the methods. This suggests that the need

Table 5. SOC stock (Tg) by estimation method and difference (%) between estimation methods.

Spatial distributing method	M+J all soils BD estimate (A)	M+J order-specific BD estimate (B)	Van Hove BD estimate (C)	% difference (A – B)	% difference (A – C)	% difference (B - C)
SOC density nearest pedon (D)	127.0	127.6	133.4	–0.5[a]	–4.9[b]	–4.4[b]
Mean SOC density per soil type, region (E)	128.3	128.8	134.9	–0.4[b]	–5.1[b]	–4.6[b]
Mean SOC density per soil–lu/lc class (F)	125.6	126.4	133.2	–0.7[d]	–5.9[d]	–5.2[d]
% difference (D – E)	–1.0[c]	–1.0[c]	–1.1[c]			
% difference (D – F)	1.1[d]	0.9[d]	0.2[d]			
% difference (E – F)	2.1[d]	1.9[d]	1.3[d]			

[a] $P = 0.02$; [b] $P < 0.01$; [c] difference is not statistically significant. [d] No statistics run because large number of cases (>10^6) reduce significance of statistical test.

BD = bulk density; M+J = Manrique & Jones (1991).

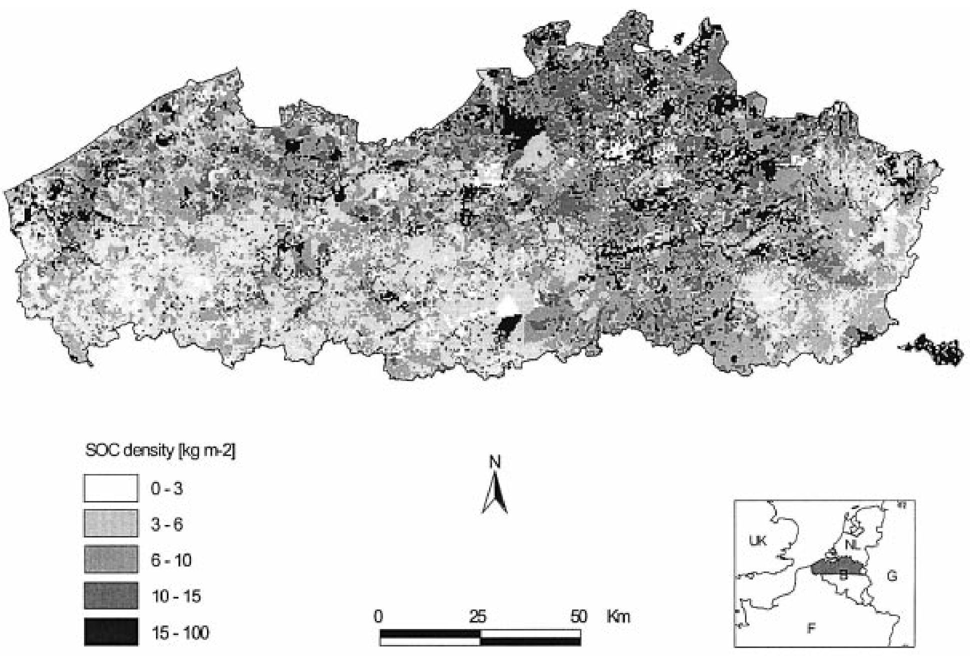

Figure 2. Distribution of SOC in Flanders.

for standardized SOC stock estimation procedures may be less than the need for high quality data sets that reduce estimation uncertainty.

Distribution of SOC in Flanders

Patterns on the SOC distribution map for Flanders reflect the SOC density of the spatially dominating soil types (Figure 2). Along the coast, in the west, and in a major river valley on the southwestern coastal plain, the map shows high SOC densities because of wet and clayey soils. In the western half of the territory, away from coastal areas, SOC densities are high in the north because wet sand and silty sand soils rich in SOC frequently occur, whereas in the south of this region SOC densities are low because humid silt soils dominate. In an area stretching north–south just east of the centre of the map, high SOC densities are observed. In the northern part of this area these high densities are due to the wet sand soils with humus B horizons, while in the southern part of the area a shallow clayey substrate appears to affect SOC density. Low SOC densities in the extreme northeast of Flanders coincide with dry sandy soils, some of which are gravelly, and low densities in the southeast coincide with dry silt soils. A SOC distribution map based on soil type–lu/lc categories, although more fragmented, enhances some of these patterns (map not presented here). The high SOC densities in the north are associated with the dominance of forests and pastures, and in the south of the western section of Flanders low SOC densities are accentuated by the prevalence of cropland (Table 4). These corroborating observations indicate that a large proportion of SOC in Flanders is stored in sandy soils in the north of the territory. Consequently, disturbance of soils or changes in lu/lc would potentially release more SOC in this area than elsewhere in Flanders.

CONCLUSIONS

Bulk density is a vital soil property that is often lacking in soil databases and, consequently, has to be estimated if the databases are to be used for SOC stock assessment. In the present study mean BD estimates differ by up to 7.5% depending on the estimation model used. This difference leads to a variation of up to 6% in the total SOC stock estimate for Flanders. These differences highlight the importance of complete and high-quality soil databases that do not require estimation of vital soil characteristics, and of robust estimation procedures if these characteristics are lacking. When a soil map alone is used as the geographical reference for various spatial distributing methods, a difference of no more than 1% in total SOC stock results. When the soil map is combined with a lu/lc map, results for total SOC stock are consistently smaller (≤2%) than when a soil map alone is used. Consequently, variation in the total SOC stock estimate due to the use of different spatial distributing methods (≤2%) is smaller than that due to the estimation of BD (<6%), and much smaller than published errors for this type of study (9–50%). This indicates that the effect of the spatial distributing method on estimated SOC stock is secondary to the quality of the data, and that the need for standardized spatial distributing methods is less important than the need for high quality databases. The maximum variation in total SOC stock between any two SOC estimation methods is 7% in the present study. This difference is comparable to the maximum variation in stock estimate resulting from the analysis of various soil databases and spatial aggregation methods for other regions

The SOC density for pedons in the database varies greatly (CV = 76%), which is not unusual for large scale studies. The SOC density is influenced by drainage class, most clearly when chemical reduction is present, texture, especially clay content, and lu/lc. The total SOC stock estimates for Flanders range from 125.6 to 134.9 Tg, depending on the estimation procedure. In the context of soils as a source or sink for greenhouse gases, this implies that an increase of only 1% in the SOC in Flanders would more than offset the 1 Tg of C released into the atmosphere by industrial processes in 1999 (Federal Department of the Environment 2002). Conversely, a loss of 1% of the SOC in Flanders would release more C into the atmosphere than industrial processes in 1999. A map of the distribution of SOC density shows that a large proportion of the SOC is stored in sandy soils in the north of Flanders. Thus, this area deserves particular attention as the potential for release of C to the atmosphere due to disturbance of soils or changes in lu/lc is greatest in this area.

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