Soil organic carbon–stock changes in Flemish grassland soils from 1990 to 2000

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Abstract
Total soil organic-carbon (SOC) stocks for grassland soils in Flanders (N Belgium) were determined for the Kyoto Protocol reference year 1990 and 2000 in order to investigate whether these soils have been CO2 sinks or sources during that period. The stocks were calculated by means of detailed SOC datasets, which were available at the community scale for the whole of Flanders. The total SOC stocks for Flemish grassland soils (1 m depth) were estimated at 38 Mt SOC in 1990 and 34 Mt SOC in 2000. The loss of SOC resulted from a decrease in the SOC content of grassland soils (71%) and could also partly (29%) be explained by a decline in grassland area. Significant decreases in %SOC for the 0–6 cm depth layer were found for the 1990s for the coarser-textured soils with SOC losses ranging between –0.3% and –0.5% over the 10 y period. Specific management practices that disturb the SOC balance such as conversion to temporary grassland and a reduction of animal-manure application are hypothesized to have contributed to the observed loss of SOC stocks. We furthermore conducted an analysis of uncertainty of the 1990 and 2000 grassland SOC–stocks calculation using Monte Carlo analysis. Probability-distribution functions were determined for each of the inputs of the SOC-stock calculation, enabling us to assess the uncertainty on the 1990 and 2000 SOC stocks. The frequency distributions of these simulated stocks both closely approached lognormal distributions, and their 95%-confidence intervals ranged between 150% and 50% of the calculated mean SOC stock. The standard error on the measured decrease in SOC stocks in Flemish grassland soils during the 1990s was calculated to be 7–8 Tg SOC, which is equivalent to twice this decrease. This clearly shows that large-scale changes in SOC stocks are uncertainty-ridden, even when they are based on detailed datasets.

Key words: grassland soils / soil organic-carbon stocks / C sequestration / Flanders / Monte Carlo analysis / uncertainty analysis

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1 Introduction

Next to efforts to reduce the emission of their greenhouse gases, countries can reach their commitments to the Kyoto Protocol (during the first Kyoto commitment period 2008–2012) by enhancing C sequestration in soils. Particularly article 3.4, which allows accounting of net changes in greenhouse-gas emissions through additional human activities related to agricultural soils, forest management, and revegetation, is of importance for grassland ecosystems.

Overall, soils of agro-ecosystems are C-depleted and represent a potential CO₂ sink. The European Climate Change Programme (ECCP) estimated an overall potential for greenhouse-gas mitigation by agricultural soils via C sequestration by up to 60–70 Tg CO₂ y⁻¹ during the first Kyoto commitment period. This corresponds to 1.5%–1.7% of the EU's anthropogenic CO₂ emissions and to 19%–21% of the total reduction of 337 Tg CO₂ y⁻¹ to which the EU is committed during that period (ECCP, 2003).

To determine the possibilities of article 3.4 and to assess the impact of land use and land use–change activities, it is necessary to have accurate soil organic-carbon (SOC) stocks for the Kyoto reference year 1990. Establishing a baseline SOC stock for 1990 is crucial to determine whether agricultural land is a sink or a source for CO₂. In Belgium, this kind of information for grassland ecosystems is absent. Even at the European level, there is little information available with regard to the total C-sequestration potential for increasing SOC stocks in grasslands soils and of the limiting factors (ECCP, 2003).

This study presents estimates for Flemish grassland SOC stocks up to 1 m depth for the Kyoto reference year 1990 and for 2000 and assessed whether the Flemish grassland area had been a sink or a source of C during this period. Possible causes for changes in the SOC stocks are discussed. Uncertainty on estimates of the changes in SOC is a requirement.
for national scale accounting and reporting to the United Nations Framework on Climate Change and the Kyoto Protocol (IPCC, 2000). Monte Carlo analysis is one of the most commonly used probability-based techniques that warrant a quantitative characterization of variability and uncertainty. A secondary objective of this study was to include a measure of the uncertainty on the grassland 1990 and 2000 SOC stocks using Monte Carlo analysis.

2 Materials and methods

2.1 Study Area

The study area, Flanders, is situated in the N of Belgium (Fig. 1) and has a temperate humid climate with a mean temperature of 9.8°C and mean annual precipitation of 780 mm (Royal Meteorological Institute, 2005). The total area of Flanders is approx. 15,000 km², almost half of the total surface of Belgium. In Flanders, different agro-pedological regions (Fig. 1) are distinguished by soil type (dominant soil texture) and by the crops cultivated. The following agro-pedological regions are considered in order of appearance from the coast to the inland: the Dunes (sand), the Polders (clay), the Sandy Region (sand), the Sandy Loam Region (sandy loam, silt loam), the Silt Region (silt), the Campines (sand), and the Pasture Area of Liege (silt). The Dunes region consists of calcareous sandy soils without soil-profile development; pasture occurs in dune dips and in the transition area to the Polders. The Polders region has clay or heavy-clay soils, often calcareous, with limited soil-profile development; soils are moderately wet to very wet and are suitable for highly demanding crops and pastures. In the Sandy Region, the dominant soil type is sand with a clear or crumbled Bw horizon; suitable for cropland and pasture and used for the cultivation of trees. In the Sandy Loam Region, soils range from light sandy-loam soils (dry to moderately wet) to sandy-loam soils (moderately wet to very wet) with a Bt horizon; used as cropland, pasture, horticulture, and fruit farming. Dry silt soils with a Bt horizon are found in the Silt Region and are mainly used for cropland, orchards, and pasture in the wetter parts. The Campines region has sandy soils with a clear Bw or Bh horizon and peat bogs with an anthropogenically altered A horizon which are suitable for cropland and grassland production and forestry. The silty soils in the Pasture area of Liege are moderately dry to moderately wet with a Bt horizon and are used as pastures and orchards (Ameryckx et al., 1995).

2.2 Grassland-area data

Statistical data on permanent grassland as well as on temporary grassland-area land use are published annually by the National Institute of Statistics at the community scale (NIS, 1991, 2001). The temporary grasslands which are only mown and not grazed have been included previously in SOC-stock calculations for cropland soils (Sleutel et al., 2003b) and were not included here. Permanent grasslands are defined here as grasslands which are at least 5 y old (EU Directive 796/2004), whereas temporary grasslands are considered to be 4 y old or younger or fields which are resown annually or biannually.

2.3 Soil–organic carbon data

We made use of a very large database of SOC measurements, generated by the Soil Service of Belgium (Hendrickx et al., 1992; Vanongeval et al., 2000), which covers the whole of Flanders. In total, 17,453 soil samples on grassland were...
taken between 1989 and 1991, and 11,502 soil samples were taken between 1998 and 2000. We used these two datasets in the calculation of the 1990 and 2000 grassland SOC stocks. Furthermore, SOC data were available for 1993 (13,409 samples) and 1996 (13,201 samples), and these data were used in a regression analysis of the %SOC (percent organic carbon) of Flemish grasslands soils against time on a community level (see below). However, no total grassland SOC stocks for these years were calculated. The %SOC was measured on samples which were taken to a depth of 6 cm. The SOC data were available to us as means plus standard deviation at the postal community scale and were grouped for this study according to the agro-pedological regions. If a postal community stretched over two or more different agro-pedological regions, a mean value with a standard deviation was available per agro-pedological region for that specific postal community. The SOC content of the samples was determined by the Walkley and Black (1934) method.

2.4 Bulk-density measurements

Bulk density was measured by Plant Unit–ILVO on grassland fields in the different agro-pedological regions. Bulk density was measured at 0–10, 10–30, and 30–60 cm depth and determined by the use of a Kopecky bore and rings with a fixed volume. Samples were oven-dried for 2–3 d at 80°C. For the extrapolation of the topsoil (0–6 cm) %SOC to 100 cm depth (see below for a description), one average bulk density representing the 0–100 cm profile was used. A weighted mean of the bulk densities measured at the different depth intervals was calculated and used as the bulk density required in the extrapolation model (Tab. 1). Bulk density for the Dunes was unavailable because no samples were taken in that region. Instead the bulk density of the Campines was used because both regions have a similar sandy soil texture.

2.5 Extrapolation of SOC data to 1 m depth

In national or regional surveys, SOC has most often been calculated to 1 m depth. In reality, regional databases are often limited to SOC data of the surface layer and extrapolation models are needed (Nakane, 1976; Bernoux et al., 1998; Jobbagy and Jackson, 2000; Hilinski, 2001) to extrapolate surface SOC stocks to 1 m depth (or more).

We used the model by Hilinski (2001), which is applied in the current version of the CENTURY soil–organic matter computer model:

\[ C(z) = C_b + (C_0 - C_b) e^{-kz} \]

where

- \( C(z) \) represents the SOC concentration (in kg C/kg dry soil\(^{-1}\)) at a depth \( z \) (m),
- \( C_b \) is the SOC concentration at the bottom of the profile,
- \( C_0 \) is the SOC concentration at the upper layer of the profile,
- \( k \) (m\(^{-1}\)) is a parameter representing the exponential decrease in SOC content with depth.

The parameter \( k \) was estimated via nonlinear regression from a series of SOC profiles which we collected for this study between 2001 and 2004. More than 1,500 samples were taken at three different depths (0–10, 10–30, and 30–60 cm) covering the different agro-pedological regions. Soil organic C was determined by the method of Walkley and Black (1934), and a compensation factor of 1.33 was used for the incomplete oxidation (75%) to recalculate the measured %SOC to total SOC content (Batjes, 1996). However, because no samples were taken from below 60 cm, for the intervals 60–80 and 80–100 cm, average SOC concentrations from the “Aardewerk” database (Van Orshoven et al., 1988) were calculated per agro-pedological region. This database was generated during the Belgian National Soil Survey (1947–1962) and contains over 10,000 full soil-profile descriptions for different land uses on different soil types. It was assumed that the SOC concentrations at these depths had remained the same between 1947–1962 and 1990–2000. This was also observed by Schlesinger (1996) and Degryze et al. (2004), who both found that the SOC concentration at such depths did not change after such time periods.

The depth \( z \), needed as input for the depth-distribution model, was taken as the middle of the sampled depth interval. Values for the parameter \( k \) were estimated for every agro-pedological region (Tab. 1), except for the Dunes. Instead, the parameter \( k \) from the Campines was used for the Dunes as both regions have a similar sandy soil texture. The parameter \( k \) varied among the agro-pedological regions, and there was a general trend towards a higher value for heavier textures.

For the calculation of the total SOC content to 1 m depth, an integration formula (Sleutel et al., 2003a) was used:

\[
\text{Total SOC (0–1 m) (kg C m}^{-2}\text{)} = \rho_b (1 - e^{-zk}) k^{-1} (C_b - C_0) + z \rho_b C_{ip}
\]

where \( \rho_b \) is the weighted mean bulk density for the whole soil profile (kg m\(^{-3}\)) for a specific agro-pedological region (Tab. 1). For the SOC concentrations in the upper layer of the profile \( (C_0) \), the SOC data from the database of the Soil Service of Belgium were used, respectively for 1990 and 2000. For the SOC concentration at the bottom of the profile \( (C_b) \), the SOC data for the interval 80–100 cm from the “Aardewerk” database were used, assuming that the SOC content at such depth had remained unchanged since the 1950s. Monte Carlo analysis was performed on this formula (see further) and therefore all parameters \( (\rho_b, C_{ip}, C_0, \text{ and } k) \) were taken into account. To calculate the total SOC stock to 1 m depth for a given agro-pedological region, the SOC content to 1 m was multiplied by the grassland area considered.

2.6 Statistical analysis

For all statistical analyses, S-plus 6.1 (Insightful Corporation, USA) was used. Normality and homogeneity of variances tests were performed with the Kolmogorov-Smirnov and Levene tests. The conditions of normality and equal var-
variances were fulfilled. Analysis of variance testing (ANOVA) with post-hoc test (Tukey) was performed to assess significant differences in %SOC between 1990, 1993, 1996, and 2000 (only the differences between 1990 and 2000 are shown) with a level of significance set at 0.05.

2.7 Change of soil organic carbon with time

A Weighted Least Square (WLS) linear regression (Neter et al., 1996) was used to analyze the change of %SOC (0–6 cm) against time. This kind of linear regression was used to take into account the large standard deviations on the SOC data which were available as means. For this WLS regression, all SOC data (1990, 1993, 1996, and 2000) from the database of the Soil Service of Belgium for the different periods were used. The 1990s SOC change flux (g OC kg⁻¹ y⁻¹) was calculated from the WLS regression: SOC = β₀ + β₁t, where β₀ is the intercept and β₁ the flux in g OC kg⁻¹ y⁻¹.

2.8 Monte Carlo simulations

Monte Carlo analysis is a stochastic method that generates multiple results of a model based on randomly selecting each input value from probability-distribution functions (PDFs). The PDFs characterize the likelihood that uncertain model input values fall within a given interval and as such are determined by the inherent variability and uncertainty of the input values. In this study, the parameters that were assumed to be uncertain were SOC concentration, Cᵢ, and k parameters of the depth-distribution function and the soil bulk density. Monte Carlo analysis with a latin hypercube sampling was used to combine the output of multiple simulations of the model at the community scale to produce a probability distribution of soil OC stock at the scale of agro-pedological regions in the study area and at the regional level.

The %SOC data, which were available as means and standard deviations at the community level were replaced by normal PDFs. The cut-off for these distributions was set at zero (i.e., soils cannot have negative SOC contents). In most cases, the variability on environmental variables which have a close to zero value, is exhibited in positively skewed distributions (Parkin and Robinson, 1992). The k and C₀ parameters were represented by lognormal distributions, based on their estimated mean and corresponding standard deviation. The k-parameter lognormal PDFs were truncated with a greater-than-zero lower limit because unrealistically high SOC stocks were calculated in simulations where close-to-zero values were sampled in Monte Carlo analysis. Lognormal PDFs were fitted to the measured bulk-density data. All data were collated and grouped per agro-pedological region in Excel data spreadsheets. Monte Carlo analysis was conducted using @RISK4.5.5 (Palisade Corp., NY, USA).

3 Results and discussion

For 1990 and 2000, the SOC stock was estimated at 38 Mt SOC and 34 Mt SOC, respectively. The greatest decrease in SOC stock between 1990 and 2000 occurred to the E and N of Brussels (Brussels is in the mid S of Flanders) and in the Campines (NE of Flanders). The NE and W parts of Flanders contained the largest SOC stocks. These regions are characterized by a large grassland surface and have a history of substantial manure application due to intensive livestock production. A general trend of declining SOC stocks was found for all agro-pedological regions (Tab. 2). The SOC content for the Dunes was very high when considering its sandy soil texture. Only the dune swales and the transition areas in the Dunes are suitable for pasture. The very limited number of samples that were taken in this region may be a reason.

The decrease in SOC stock can mainly be explained by a decrease in g OC kg⁻¹ (responsible for 71% of the decrease) and less so by a decline in grassland area (responsible for 29% of the decrease). The grassland area in 1990 was 238,173 ha and decreased by 3% to 230,199 ha in 2000 (NIS, 1991, 2001). This decrease in grassland area was complemented by an enormous increase in maize production of 37% between 1990 and 2000 (NIS, 1991, 2001). In addition.

Table 1: Soil bulk density (ρ_b) (± standard deviation), estimated k parameter of the depth-distribution model (k) (± standard deviation), and R² of the model fit and number of profiles (n) (data taken from Mestdagh et al., 2004), 1990 and 2000 grassland area (ha) and calculated 1990 and 2000 SOC content up to 1 m (± standard deviation) for the different agro-pedological regions of Flanders (Belgium).

<table>
<thead>
<tr>
<th>Agro-pedological region</th>
<th>ρ_b (g cm⁻³)</th>
<th>k (m⁻¹)</th>
<th>R² fit k</th>
<th>n</th>
<th>Grassland area (ha)</th>
<th>Mean SOC content (kg OC m⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campines</td>
<td>1.42 ± 0.17</td>
<td>2.56 ± 1.46</td>
<td>85</td>
<td>310</td>
<td>53788</td>
<td>52935</td>
</tr>
<tr>
<td>Silt Region</td>
<td>1.47 ± 0.09</td>
<td>3.86 ± 1.72</td>
<td>93</td>
<td>60</td>
<td>11771</td>
<td>11412</td>
</tr>
<tr>
<td>Polders</td>
<td>1.52 ± 0.11</td>
<td>3.34 ± 1.46</td>
<td>93</td>
<td>255</td>
<td>21679</td>
<td>20981</td>
</tr>
<tr>
<td>Sandy Loam Region</td>
<td>1.48 ± 0.18</td>
<td>3.30 ± 1.60</td>
<td>90</td>
<td>930</td>
<td>72451</td>
<td>68724</td>
</tr>
<tr>
<td>Sandy Region</td>
<td>1.47 ± 0.07</td>
<td>2.91 ± 1.42</td>
<td>89</td>
<td>230</td>
<td>73458</td>
<td>71795</td>
</tr>
<tr>
<td>Dunes</td>
<td>1.42 ± 0.17</td>
<td>2.71 ± 1.42</td>
<td>90</td>
<td>230</td>
<td>73458</td>
<td>71795</td>
</tr>
<tr>
<td>Pasture Area of Liegea</td>
<td>2327</td>
<td>1864</td>
<td>18.1 ± 4.4</td>
<td>16.0 ± 3.6</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

a Insufficient data: ρ_b of Pasture Area of Liege taken equal to the measured ρ_b of the Silt Region
b Insufficient data: the k parameters of Dunes and Pasture Area of Liege were taken equal to the k parameters of the Campines and the Silt Region, respectively

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there was a decrease in livestock numbers by 9.2% during that period.

Overall, there was a decrease in mean SOC content from 15.8 kg OC m$^{-2}$ in 1990 to 14.3 kg OC m$^{-2}$ in 2000. This loss of $-0.15$ kg OC m$^{-2}$ y$^{-1}$ is in line with the results found by Bellamy et al. (2005), who also found a C loss in the soils under rotational and permanent grass, under rough grazing, and in upland grass across England and Wales. However, the results of both studies are in contrast to the future flux (2008–2012) of +0.05 kg OC m$^{-2}$ y$^{-1}$ for European grassland soils that was estimated by Vleeshouwer and Verhagen (2002) for a “business as usual” scenario. The decreasing trend in g OC kg$^{-1}$ between 1990 and 2000 in Flanders was significant for all regions ($p < 0.05$), except for the Polders, the Dunes, and the Pasture Area of Liege (Tab. 3). For these three regions, which comprise only 11% of the total grassland surface, the regressions were not significant because of the smaller relative magnitude of these changes in SOC compared to the variability on the SOC data.

The observed decrease in g OC kg$^{-1}$ may be explained by several factors. One of the possible explanations for the decrease in SOC content per m$^2$ might have been the approval of the Manure Action Plan (MAP) in Flanders by which the application of N via chemical fertilizer and manure was limited at the beginning of the 1990s. Before 1990, the applied amounts of nutrients were unrestricted, while in 1999, the maximum application allowed was set at 450 kg N ha$^{-1}$ y$^{-1}$. As such, the MAP may have contributed indirectly to a loss of SOC because of a limitation of the supply of fresh OM to the soil through animal manure. In contrast, Van Meirvenne et al. (1996) found an increase of 25% in the topsoil SOC in W-Flemish croplands between 1960 and 1990 due to SOC in the use of pig slurry. The approval of the MAP can be a possible reason, however, other factors may have been involved in the large decreases in SOC content of these soils. The share of temporary grassland within the total grassland area increased from 11% in 1990 to 22% in 2000 (NIS, 1991, 2001). Temporary grassland generally has significantly lower SOC contents compared to permanent grassland (Mestdagh et al., 2006). The intensity of the temporary grassland management is crucial to the resulting equilibrium in SOC stock, and therefore these large land-use conversions undoubtedly must have contributed to the observed losses of SOC stocks.

The potential of grasslands to become sinks instead of sources of CO$_2$ will therefore have to include the recovery of grassland area lost and increasing the SOC content of grassland soils by management practices which build up OC in the soil. To calculate the amounts of OC that could be stored by converting cropland to grassland, C-sequestration rates for

### Table 2: Estimate of uncertainty of 1990 and 2000 SOC stocks in grassland soils of Flanders (kt OC).

<table>
<thead>
<tr>
<th>Agro-pedological region</th>
<th>1990 mean</th>
<th>2.5th percentile</th>
<th>97.5th percentile</th>
<th>95% range</th>
<th>Skewness</th>
<th>Kurtosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campines</td>
<td>8801</td>
<td>4644</td>
<td>15,287</td>
<td>10,643</td>
<td>1.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Pasture Area of Liege</td>
<td>7579</td>
<td>3980</td>
<td>13,156</td>
<td>9176</td>
<td>1.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Dunes</td>
<td>1493</td>
<td>797</td>
<td>2600</td>
<td>1803</td>
<td>1.0</td>
<td>4.6</td>
</tr>
<tr>
<td>Sandy Region</td>
<td>1309</td>
<td>687</td>
<td>2261</td>
<td>1574</td>
<td>1.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Polders</td>
<td>4327</td>
<td>2537</td>
<td>7056</td>
<td>4519</td>
<td>0.9</td>
<td>4.6</td>
</tr>
<tr>
<td>Sandy Loam Region</td>
<td>11,003</td>
<td>5963</td>
<td>18,699</td>
<td>12,736</td>
<td>1.0</td>
<td>4.7</td>
</tr>
<tr>
<td>Silt Region</td>
<td>9599</td>
<td>6667</td>
<td>13,153</td>
<td>6286</td>
<td>0.6</td>
<td>3.6</td>
</tr>
<tr>
<td>Sandy Region</td>
<td>11,034</td>
<td>6454</td>
<td>17,700</td>
<td>11,246</td>
<td>0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Polders</td>
<td>10,006</td>
<td>6311</td>
<td>15,368</td>
<td>9057</td>
<td>0.8</td>
<td>4.1</td>
</tr>
<tr>
<td>Dunes</td>
<td>609</td>
<td>351</td>
<td>986</td>
<td>635</td>
<td>0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Pasture Area of Liege</td>
<td>609</td>
<td>351</td>
<td>986</td>
<td>635</td>
<td>0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Sandy Region</td>
<td>609</td>
<td>351</td>
<td>986</td>
<td>635</td>
<td>0.8</td>
<td>4.3</td>
</tr>
<tr>
<td>Flanders</td>
<td>38,332</td>
<td>28,836</td>
<td>50,067</td>
<td>21,231</td>
<td>0.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Campines</td>
<td>33,695</td>
<td>26,909</td>
<td>42,313</td>
<td>15,404</td>
<td>0.5</td>
<td>3.5</td>
</tr>
</tbody>
</table>

### Table 3: Results of the linear regression against time of the topsoil SOC content (0–6 cm depth layer) and the 1 m depth–extrapolated SOC-stock change for the different agro-pedological regions of Flanders (Belgium).

<table>
<thead>
<tr>
<th>Agro-pedological region</th>
<th>$b_0$ (g OC kg$^{-1}$)</th>
<th>$b_1$ (g OC kg$^{-1}$ y$^{-1}$)</th>
<th>SOC-stock change (kg OC m$^{-2}$ y$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campines</td>
<td>30.410</td>
<td>-0.455 **</td>
<td>-0.0374</td>
</tr>
<tr>
<td>Silt Region</td>
<td>31.359</td>
<td>-0.432 *</td>
<td>-0.0358</td>
</tr>
<tr>
<td>Polders</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sandy Loam Region</td>
<td>31.603</td>
<td>-0.311 **</td>
<td>-0.0250</td>
</tr>
<tr>
<td>Sandy Region</td>
<td>30.119</td>
<td>-0.302 **</td>
<td>-0.0245</td>
</tr>
<tr>
<td>Dunes</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Pasture Area of Liege</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

a level of significance of the regression: **: $p < 0.01$ ; *: $p < 0.05$ ; -: not significant
the conversion of arable land into grassland from Post and Kwon (2000), Vleeshouwer and Verhagen (2002), and Arrouays et al. (2002) were used. The smallest rate has been given by Post and Kwon (2000) with 0.033 kg C m$^{-2}$ y$^{-1}$ and the highest by Vleeshouwer and Verhagen (2002) with 0.144 kg C m$^{-2}$ y$^{-1}$. If Flanders would be able to recover the loss of 7,973 ha grassland (Tab. 1) between 1990 and 2000, it would be possible to sequester between 2,647 t C (9,714 t CO$_2$ eq.) and 11,481 t C (42,135 t CO$_2$ eq.). These amounts are still far off from the total required CO$_2$-emission reduction (78 Mt CO$_2$ eq.) to which Belgium has committed itself under the Kyoto Protocol.

3.1 Uncertainty analysis

Table 2 summarizes the results of 10,000 Monte Carlo simulations of the 1990 and 2000 grassland SOC stocks of the agro-pedological regions and of Flanders as a whole. All PDFs of the SOC stocks of the different agro-pedological regions approached the lognormal distribution and were only slightly skewed to the right (Fig. 2). The uncertainty on the calculated SOC stocks was as large as the 95% range spread from about 50% to 150% of the calculated mean SOC stock (Tab. 2). The agro-pedological regions contributed to the total uncertainty in the order: Campines > Sand Region > Sandy Loam Region > Polders > Silt Region, which is largely associated with the grassland surfaces in these regions. Considering the individual factors involved in the calculation of the SOC stocks, the largest contribution to the total uncertainty on the Flemish SOC stocks came from the depth extrapolation of the topsoil SOC measurements (50%) (i.e., from the parameters $k$ and $C_B$). Sensitivity analysis showed that uncertainty on the soil bulk-density data ($\rho_b$) contributed 28% and the contributions of the community SOC data summed to 22%. In order to reduce the uncertainty on future SOC-stock calculations, efforts should be put into reducing errors associated with depth extrapolation of SOC measurements. This could be achieved by measuring SOC in deeper soil layers but this would inverse expenses. Alternatively, refinement of the regions for which such depth-distribution models are fitted (here we used one parameter set per 30,000 ha on average) could reduce uncertainty as well. Furthermore, this analysis points to the value of accurate regional soil bulk-density data-sets, which may be assessed at a relative low extra cost along with a soil survey aimed at measuring regional SOC stocks.

The bulk density is rarely measured in extensive soil surveys, and it was not measured in our study neither. When soil bulk density changes as a result of swelling or compaction, fixed-depth methods may not adequately quantify SOC-stock changes. In order to completely offset the observed measured decrease in SOC levels (Tab. 3), an increase in the average soil bulk density from 1.46 g cm$^{-3}$ towards 1.61 g cm$^{-3}$ should have taken place. Impacts of mechanization, changes in SOM levels and appreciable shifts in net inputs of materials such as organic wastes and livestock manure (Chang et al., 2007) all might have affected the soil bulk density. First, while mechanization has steadily intensified since the 1950s, there was no further substantial increase in weight of machinery during the 1990s. Next, the measured loss of SOC levels per se might also have led to increased bulk density since both have an inverse relationship as for example in the frequently used equation by Rawls (1983). However, based on this relation, a relative decline in SOC content by approx. 12%, as observed in this study, would have resulted in a relative increase in soil bulk density by merely 1.5%, i.e., +0.01 g cm$^{-3}$. Given the relatively large standard deviation on the bulk density PDFs, we assume that a potential error introduced by not considering these (potential) systematic changes in bulk density was covered satisfactorily by the Monte Carlo analysis.

A Monte Carlo approach has been used earlier to estimate uncertainty on predictions of SOC-stock changes in agricultural land over a 15 y period in the US (Ogle et al., 2003) and over a 10 y period in Canada (VandenBygaart et al., 2004). In contrast to our approach, however, these authors estimated...
the effects of management on SOC stocks based on “management factors” in a modified IPCC methodology. VandenBygaart et al. (2004) calculated an increase in SOC stocks of 5.7 Tg C y\(^{-1}\) with an almost equally large 95%-confidence range of 5.1 Tg C y\(^{-1}\) while Ogle et al. (2003) calculated an increase in SOC stocks of 1.3 Tg C y\(^{-1}\) with a tenfold 95%-confidence range of 11.3 Tg C y\(^{-1}\). Taking the large uncertainty on regional-scaled SOC-stock estimates for 1990 and 2000 in our study, the standard error on a difference in Flemish grassland SOC stock between the two surveys was estimated at 7–8 Tg SOC. Considering that this value equals almost twice the observed loss of SOC from grassland soils of 4 Tg during the 1990s, this uncertainty is very large but it matches the ranges of uncertainty on SOC-stock estimates found in the studies by VandenBygaart et al. (2004) and Ogle et al. (2003).

4 Conclusions

We can state that although this study revealed that grassland soils in the study area have been a significant source of CO\(_2\) during the 1990s (the total SOC stocks decreased from 38 Tg in 1990 to 34 Tg in 2000), large uncertainty on such estimates may obstruct assessment of even large stock changes. As revealed by Monte Carlo analysis, the estimated standard error on the observed loss of SOC from grassland soils amounted twice this decrease. This study thereby quantitatively demonstrates that dataset uncertainty restricts the unequivocal assessment of changes in SOC stocks on a regional scale. This has direct consequences for future large-scale verifiability and accounting of SOC sequestration based on regional level soil surveys. Likely factors to have brought about these changes in SOC stock in Belgium may involve the reduction of the amounts of manure applied to grassland with the establishment of a nutrient legislation and by the expansion of the temporary pasture usage. However, as was the case for this study, past-management data will often be lacking to confirm such hypotheses.

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