Estimates of carbon stock changes in Belgian cropland

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Abstract. Article 3.4 of the Kyoto Protocol allows carbon emissions to be offset by demonstrable removal of carbon from the atmosphere by improved management of agricultural soils. To make use of this possibility, a good estimate of soil organic carbon (SOC) stocks and baseline emissions (in 1990) are crucial factors. Over 210,000 topsoil (0–24 cm) measurements have been made in Belgian cropland in the period 1989–1999, which are available for seven different agro-pedological regions and for three periods (1989–91, 1992–95, 1996–99). We used this extensive SOC data set to estimate SOC stocks and fluxes in Belgian cropland. The measurements of SOC were extrapolated to 1 m depth using an exponential SOC depth distribution model, based on another large data set of over 5184 fully described soil profiles on Belgian cropland made during the National Soil Survey. The SOC data were combined with cropland area figures to calculate SOC stocks to 1 m depth. The 1990 baseline SOC flux of Belgian cropland was then obtained using two different calculation methods, which each yielded similar results and showed that SOC stocks were decreasing in the 1990s at a mean rate of 608 kton OC yr⁻¹. Consequently, a large part of the Belgian cropland acted as a net source of CO₂ emissions during the period 1989–1999.

Keywords: Carbon stock, carbon depth distribution, carbon sequestration, Kyoto Protocol, net-net approach, Belgium

INTRODUCTION

In the context of global warming, agriculture is discussed both as a source of greenhouse gases (CO₂, CH₄ and N₂O) as well as a potential sink for atmospheric CO₂. Agriculture could help in slowing down the accumulation of these gases, either by emission reduction, or by sequestering part of the atmospheric CO₂ in soil organic matter (Sauerbeck 2001). By ratification of the Kyoto Protocol, Belgium has committed itself to a 7.5% reduction in CO₂ emissions compared with baseline levels (1990) during the first commitment period (2008–2012). Article 3.4 (‘Land Use, Land Use Change and Forestry’, LULUCF – activities related to agriculture and forestry) allows carbon emissions to be offset by demonstrable removal of carbon from the atmosphere by improved management of agricultural soils. A country may choose which additional human-induced activities related to changes in greenhouse gas emissions and removals from agricultural soils are to be accounted for, provided that they have been implemented since 1990. As stated in the Kyoto Protocol, during the first commitment period 2008–2012, these net emission reductions are to be accounted for using a ‘net-net approach’; that is, accountable emission reduction should equal 5 times the CO₂-equivalents emission in 1990 minus the total CO₂-equivalents emission during the 5-year period 2008–2012.

Obviously, the use of this methodology poses a problem of data availability and data quality with respect to 1990 greenhouse gas emissions: the accuracy of this data is an important criterion for the net-net approach. No country has actually measured these 1990 baseline greenhouse gas fluxes and the question is then whether it is possible to make these estimates retrospectively. For net CO₂ fluxes from cropland, one possible way to do this would be to determine them indirectly from the change in soil organic carbon (SOC) since 1990.

The greatest potential to increase current soil carbon stocks will probably be through improved management of agricultural land, particularly degraded croplands (Batjes et al. 1999). Increases in soil carbon are finite with systems tending towards new equilibria after 50–100 years, whereby carbon accumulation slows and eventually stops (Smith et al. 1997). Consequently, the carbon sequestration potential of a soil depends partly on the carbon stock present in that soil. Hence, there is a clear need to provide quantitative estimates of the amount of soil SOC present in the soil in 1990, not only to implement the net-net approach, but also to point out in which agricultural regions the most effort on carbon sequestration should be concentrated.

National SOC stocks and their distribution have been estimated in several countries, for example, in Great Britain.
(Howard et al. 1995), Spain (Rodriguez-Murillo 2001) and France (Arrouays et al. 2001). These estimates have been based on limited data sets: Rodriguez-Murillo (2001) based his calculations on 846 soil profiles for entire Spain; while Arrouays et al. (2001) based their SOC map of France on data of around 5000 agricultural fields. For Belgium, an enormous SOC data set is available, including 6169 fully described geo-referenced soil profiles dating back to the National Soil Survey (1947–1962) and over 200 000 topsoil (0–23.8 cm) measurements of SOC made during the period 1989–1999. This latter data set is highly relevant to establishing the 1990 SOC baseline. This article attempts to use this unique data set of SOC from Belgian cropland to estimate the baseline CO$_2$-fluxes, which are critical to the implementation of the net-net approach, using two different approaches. Although these data sets comprised the whole of Belgium, they did not contain SOC data for Wallony (the southern part of Belgium) for the baseline year 1990. Therefore, this study had to be restricted to Flanders and a part of Wallony.

MATERIALS AND METHODS

Study area

Our study area covered all Flanders (the northern part of Belgium) and the centrally located Silt Region, which includes a large part of the cropland in Wallony as well. Figure 1 shows a map of the seven different Flemish agro-pedological regions (abbreviated as: DU, Dunes; PO, Polders; SA, Sandy Region; SL, Sandy Loam Region; CA, Campines; S, Silt Region; PL, Pasture Area Liège). Flanders and the Silt Region comprise the largest part (82%) of the total cropland area in Belgium. In this article, the term ‘cropland’ is used for this 82% area of the country where, typically, annual crops are grown (e.g. sugarbeet, potato, wheat), but there are also parcels with temporary pasture and field vegetables. Cropland area for each of these regions is published annually by the National Institute for Statistics (NIS 1990).

Organic carbon data

In the period 1989–1999, on average, over 21 000 soil samples were taken annually by the Belgian Pedological Service on cropland to a depth of 24 cm. With the soil analysis data the Pedological Service provides advice on fertilizer use. Organic carbon (OC) on samples was determined by the method of Walkey & Black (1934). The analytical data were grouped by agro-pedological region and by date (1989–91, 1992–95 and 1996–99). The SOC percentage was published by Vanongeval et al. (2000) as a distribution of all samples within seven arbitrary SOC classes (data not shown). The weighed mean SOC
The analytical data, the exact location and the land use from this survey are available in digital format as a database named 'Aardewerk' (Van Orshoven et al. 1988). We assumed that the carbon concentration at the profile base, $C_b$, had remained the same between the time 1947–1962 and 1999. For every other depth, $z$, and each agro-pedological region we assumed that the SOC percentage had changed proportionally to the mean measured change in the OC percentage of the surface layer, $C_{0b}$, over this period. Only those profiles in cropland, temporary pasture or orchard were included when fitting the equation (5184 profiles). Because the OC percentage had been measured by horizon, we took $z$ as equal to the mean depth of each horizon. According to Bennema (1947) the error of using mean depths is no larger than the systematic errors attributable to the limited accuracy of the Walkey & Black determination and to the delineation of layer boundaries. Using non-linear regression, equation (1) was fitted to the 1990 carbon data, with $z$, $C(z)$, $C_b$ and $C_0$ as input variables and $K$ the parameter to be estimated.

By integrating equation (1), fitted for each region between 0 and 100 cm and multiplying by bulk density ($\rho_b$), an expression was obtained for the total OC (g cm$^{-2}$) to 1 m depth:

$$\text{Total } OC_{0\rightarrow1m} = \rho_b \int_0^{100} C(z)dz = \rho_b(1 - e^{-100K})K^{-1}(C_0 - C_b) + 100\rho_bC_b$$

(2)

A mean value for $\rho_b$ was estimated for each agro-pedological region, based on soil texture using the class pedotransfer function published by Van Hove (1969) (Figure 2), which has also been used by Van Meirvenne et al. (1996). The assumption was made that bulk density had not changed between the time of the National Soil Survey and 1999.

Calculation of the total SOC stocks according to equation (2) was evaluated using following measures: the relative mean error (ME),

$$ME = 100 \frac{\sum_{i=1}^{n}(P_i - O_i)}{\sigma}$$

the root mean square error (RMSE) (Bernoux et al. 1998),

$$RMSE = \left(\frac{1}{n} \sum_{i=1}^{n}(P_i - O_i)^2\right)^{\frac{1}{2}}$$

(3)

the coefficient of residual mass (CRM) (Loague & Green 1991),

$$CRM = \left(\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i\right)/\sum_{i=1}^{n}O_i$$

(4)

and the modelling efficiency (EF) (Loague & Green 1991),

$$EF = 1 - \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(P_i - \bar{P})^2}$$

where $O_i$ is the measured carbon content of the $i$-th profile, $P_i$ is the model prediction, $\bar{P}$ is the mean prediction, and $\sigma$ is the standard deviation of the measurements. In the case of ME and CRM, a score of 100% means a perfect fit, whereas a score of 0% means no agreement between measured and predicted values. A score of 50% would therefore indicate that the model predictions were as good as the mean of the measured values.
The depth distribution model fitted well, except for CA, PO, SA and SL, and this was due to the presence of horizons with high OC percentage below the upper horizon (e.g. spodic Bh horizons in CA and peat layers in PO). The poor fit for these profiles was expected. The model fit was greatly improved by excluding these specific profiles from the database, which represented only 5.4, 8.5, 1.8 and 0.6% of the total number of profiles for each of the above-mentioned regions, respectively. The number of profiles excluded seems acceptable, given the very large number of the remaining profiles. Values for $K$, $C_b$, $R^2$, RMSE, CRM, EF and the ME for each agro-pedological region are shown Table 1. Values for EF can be positive or negative with a maximum value of 1; since the EFs were well positive for all regions except for PO, we judged them to be acceptable. A positive value indicates that the simulated values describe the trend in the measured data better than the mean of the observations. From the values of the CRM (Table 1) it can be seen that the model slightly overestimated the OC stocks for most regions.

The $K$-values were very similar for most neighbouring regions (e.g. SA & CA; SL & S). However, there was a general trend for higher $K$-values among heavier soil textures. The lowest values were obtained for the SA and CA regions with a sandy texture (sand, loamy sand, sandy loam, according to USDA classification); slightly larger $K$-values were related to SL and S which have silt and silt-loam to loam soil textures, and the largest $K$-value was for PO where most soils have a clay texture. A larger $K$-value means a greater decrease of percentage OC with depth, and hence, the finer the soil texture the greater the decrease of percentage OC with depth. Many soils in PO tend to have higher water tables, which may explain the different K-value for PO, rather than soil texture.

Total SOC stocks per agro-pedological region are listed in Table 2, along with the estimated parameters of the linear regression of the change in mean OC with time (equation 6). By summing the estimated stocks for all regions, the total 1990 SOC stock in cropland amounted to about 49 000 kton OC. Table 2 also gives the value of the SOC flux ($\dot{b}$) expressed as the corresponding change in SOC stock for each region. No calculations could be performed for the smallest region DU, because cropland areas were not available. The regression coefficients were significant ($P=0.05$) for all regions except for PL. The total area of these two regions (DU and PL) represents no more than 0.26% of the total cropland area, and the relatively small number of samples in these regions probably explains the lack of significance.

The stock changes in 1990, calculated by the alternative method (the difference between the calculated 1993 and 1990 SOC stocks divided by 3.5), are given in Figure 3. These results show a decrease in SOC stocks for all regions, which is in agreement with the negative value of parameter $\dot{b}$. The largest regions (S, SL and SA) contribute more than 90% to this decrease. When converted to CO$_2$, a total flux of about $-2229$ kton CO$_2$yr$^{-1}$ is obtained for the whole of Belgium in 1990. The first method of calculating the flux,

Table 1. Estimated parameters of the depth distribution model and statistical evaluation by agro-pedological region.

<table>
<thead>
<tr>
<th>Region</th>
<th>$K$ (cm$^{-1}$)</th>
<th>$C_b$ (%OC)</th>
<th>$R^2$</th>
<th>RMSE</th>
<th>CRM</th>
<th>EF</th>
<th>Relative error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PO</td>
<td>0.05375</td>
<td>0.280</td>
<td>0.81</td>
<td>8.91</td>
<td>0.403</td>
<td>-0.088</td>
<td>-40.3</td>
</tr>
<tr>
<td>DU</td>
<td>0.02675</td>
<td>0.362</td>
<td>0.58</td>
<td>4.20</td>
<td>-0.112</td>
<td>0.477</td>
<td>10.9</td>
</tr>
<tr>
<td>SA</td>
<td>0.02201</td>
<td>0.037</td>
<td>0.71</td>
<td>4.97</td>
<td>0.008</td>
<td>0.901</td>
<td>-0.8</td>
</tr>
<tr>
<td>CA</td>
<td>0.02231</td>
<td>0.066</td>
<td>0.71</td>
<td>5.59</td>
<td>-0.015</td>
<td>0.597</td>
<td>1.5</td>
</tr>
<tr>
<td>SL</td>
<td>0.02521</td>
<td>0.080</td>
<td>0.81</td>
<td>2.25</td>
<td>-0.046</td>
<td>0.532</td>
<td>4.6</td>
</tr>
<tr>
<td>S</td>
<td>0.02510</td>
<td>0.131</td>
<td>0.82</td>
<td>2.32</td>
<td>0.003</td>
<td>0.722</td>
<td>-0.3</td>
</tr>
<tr>
<td>PL</td>
<td>0.02755</td>
<td>0.159</td>
<td>0.84</td>
<td>2.13</td>
<td>-0.019</td>
<td>0.750</td>
<td>1.9</td>
</tr>
</tbody>
</table>

For abbreviations, see Materials and Methods.

$$EF = \left( \frac{\sum \left( O_i - \bar{O} \right)^2 - \sum \left( P_i - O_i \right)^2}{\sum \left( O_i - \bar{O} \right)^2} \right)$$

where $P_i$ are the carbon stocks to 1 m depth predicted by the model; $O_i$ is the carbon stock to 1 m depth calculated for the same profile using the measured SOC, $n$ is the number of samples and $\bar{O}$ is the mean of all $O_i$ values.

### Calculation of the C flux

As this paper focuses on Belgian cropland for which very detailed carbon data were available for each agro-pedological region, we decided also to estimate stocks by agro-pedological region rather than to reclassify them using the Belgian soil map. An additional reason was that cropland area figures for 1990 were also available on an agro-pedological basis. Reclassifying the carbon data or using some form of kriging would bring in an additional uncertainty, because the geographical spread of the carbon and cropland area data would no longer match. Indeed, the best classification must be that which gives the smallest statistical evaluation by agro-pedological region.
from the regression parameters, yielded a similar result of −2203 kton CO2 yr⁻¹. On the basis of this data, Belgian agriculture was a net source of CO2 in 1990. Although all sampling for OC since 1990 was only to 24 cm depth, there were no indications that the ploughing depth has increased since then. We can therefore assume that the general decrease of topsoil OC content observed here represents a real decrease, and is not an artefact caused by deeper tillage. Van Meirvenne et al. (1996) reported an increase of the topsoil percentage SOC in the province of West-Flanders (Belgium) between the 1950s and 1990, which was accompanied by an increased ploughing depth (10 cm on average), resulting in a significant net increase of OC topsoil stocks. This province contains a part of the PO, SA, SL and S regions. If we assume that the results obtained by Van Meirvenne et al. (1996) are representative of the entire PO, SA, SL, and S regions, our results would indicate a change in trend. However, in West-Flanders agriculture is characterized by very intensive pig breeding and intensive field vegetable production, and therefore is probably not representative of the whole country.

Two main reasons may explain the decreasing SOC stocks. First, farmyard manure production in Belgium has become unusual because systems using straw for bedding have been replaced by systems based on slurry. The beneficial effect of regular application of farmyard manure on the percentage SOC is well known (Hofman et al. 1980; Leinweber & Reuter 1992). This decreased use of farmyard manure started well before 1990, and so the decrease in SOC stocks found here was likely already going on for a number of years before 1990. Second, animal manure application to land has decreased recently due to legal restrictions. Since 1991 in Belgium, and particularly in Flanders, regulations on the field application of animal manure have changed with the introduction of the ‘Manure Action Plan’ (MAP) in 1991. The MAP has imposed very rigorous restrictions on the use of all kinds of manure, whereas in the past all manures were spread on land, often at excessive rates. At present, Belgium is facing a large surplus of manure due to ‘non-territory-bound’ animal production. For parts of the Silt Region, the decrease of the SOC stocks reported here may also be attributed to the continued effect of historical land-use change. The Silt Region is now more focused on cropland production solely, whereas in the past mainly mixed farms existed in that region.

The quantity of 2203 kton CO2 emitted by cropland has not been added to the total Belgian greenhouse gas balance for 1990. Indeed Belgium reported 0 kton CO2 to the UNFCCC in its common reporting format, National Greenhouse Gas inventory. If this 2203 kton CO2 is included in the 13 4406 kton CO2 equivalent, already reported as the total 1990 emission for Belgium, an additional reduction of 165 kton CO2 equivalent (7.5%) will have to be accomplished.

If the decreasing trend of SOC stocks in Belgian cropland reported here continues to 2008, SOC levels may be significantly smaller at that time than in 1990. Emission reduction through changes in agricultural management would then be necessary to reverse the decline that has occurred in the period since 1990. Although CO2 emissions from agricultural land in the period 1991–2007 must also be reported according to Article 3.4, they have no direct (negative) implications when using the net-net approach. Because a smaller effort is needed to increase the SOC content of OC depleted soils, the decrease in SOC stocks before the start of the commitment period will facilitate the effort to store C in Belgian cropland starting from 2008. This means that large CO2 emissions during the period 1991 to 2008 would help Belgium in reaching its Kyoto targets, which shows one of the potential sources of error in using the net-net accounting approach.

CONCLUSIONS

Belgian cropland was shown to be a net source of CO2 in the baseline year 1990 with an emission of about 2200 kton CO2. As a consequence, Belgium will have to reduce CO2 emissions by an extra 165 kton CO2 yr⁻¹ during the commitment period, by contrast with previous calculations. Given the net-net rule, however, cropland production being a net source in 1990 also makes it easier for Belgium to claim credit, since a mere reduction of the size of this source will count as net emission reduction.

Calculating the 1990 baseline emissions using two different methodologies yielded very similar results. Many countries will have major difficulties when attempting to estimate the baseline 1990 CO2 fluxes. An approach in which
multiple years are included as a baseline, and in which emissions in the years following the baseline year are also taken into account, would be a more complete way of accounting. However, from a practical point of view, application of a more complex system may prove to be more difficult to implement than the current net-net approach, as more effort in data calculation would be needed.

ACKNOWLEDGEMENTS

This study is part of the CASTEC research project (carbon sequestration potential in different Belgian terrestrial ecosystems: quantification and strategic exploration), funded by the Belgian Federal Office for Scientific, Technical and Cultural Affairs.

REFERENCES


Received October 2002, accepted after revision February 2003.

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