Agricultural management explains historic changes in regional soil carbon stocks

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Agriculture is considered to be among the economic sectors having the greatest greenhouse gas mitigation potential, largely via soil organic carbon (SOC) sequestration. However, it remains a challenge to accurately quantify SOC stock changes at regional to national scales. SOC stock changes resulting from SOC inventory systems are only available for a few countries and the trends vary widely between studies. Process-based models can provide insight in the drivers of SOC changes, but accurate input data are currently not available at these spatial scales. Here we use measurements from a soil inventory dating from the 1960s and resampled in 2006 covering the major soil types and agricultural regions in Belgium together with region-specific land use and management data and a process-based model. The largest decreases in SOC stocks occurred in poorly drained grassland soils (clays and floodplain soils), consistent with drainage improvements since 1960. Large increases in SOC in well drained grassland soils appear to be a legacy effect of widespread conversion of cropland to grassland before 1960. SOC in cropland increased only in sandy lowland soils, driven by increasing manure additions. Modeled land use and management impacts accounted for more than 70% of the variation in observed SOC changes, and no bias could be demonstrated. There was no significant effect of climate trends since 1960 on observed SOC changes. SOC monitoring networks are being established in many countries. Our results demonstrate that detailed and long-term land management data are crucial to explain the observed SOC changes for such networks.

regional inventories | soil organic carbon dynamics modeling | land use history

The Intergovernmental Panel on Climate Change fourth assessment identified agriculture as among the economic sectors having the greatest near-term (by 2030) greenhouse gas mitigation potential, largely via soil organic carbon (SOC) sequestration (1). A major question, however, is whether SOC stock changes can be accurately quantified at regional to national scales to support effective policies (2). SOC inventory systems are being developed, but to date national-scale measurement-based inventories have not been able to clearly attribute changes in soil carbon stocks to specific land use and management and/or climate effects (3). Regional and country-wide repeated inventories of SOC have demonstrated large changes in SOC stocks during recent decades (4–7). Although most regional studies in agricultural soils report a SOC loss, some studies have also registered a gain in SOC (7) or both losses and gains depending on the land use (6). To the contrary, model-based inventories that build on detailed land use and management observations for change attribution typically lack a national network of SOC stock observations (8, 9). Hence, satisfactory explanations of historic SOC changes at the regional scale have not yet been given (3).

Recently, Meersmans et al. (10) highlighted the spatial pattern in SOC change of agricultural soil (0–30 cm topsoil) in Belgium during the past 50 y (Fig. 1). They used an empirical model derived from a dataset of 600 soil profiles in which land use had remained unchanged between 1960 and 2006 (11). SOC in cropland decreased in most regions apart from the Polder and Sand regions in the north (Fig. 1). SOC changes in grasslands show a contrasting behavior: increasing in southeastern Belgium and decreasing in the poorly drained soils in the north, particularly in riparian floodplains. The pattern of these SOC losses and gains coincided to a large extent with distinct agricultural regions (i.e., regions with a broadly similar soil type, climate, and agricultural management).

To interpret observed SOC changes during the past 50 y in agricultural soils, we stratified the SOC data of the 600 soil profiles into landscape units (LSUs) with similar soil texture, drainage class, land use, and agricultural region (*SI Text*). Only LSUs with three or more soil profiles were retained, and the main soil types in nearly all agricultural units were covered. We then applied a process-based SOC dynamic model using records of agricultural management and estimated carbon inputs to simulate the mean SOC changes from 1960 to 2006 by LSU (*Materials and Methods*). We chose the RothC-26.3 model (12), as it has performed well in predicting SOC changes by agricultural management in long-term experiments in neighboring countries using independent crop input data (13, 14). Furthermore, the input data required for the RothC model correspond to what can be realistically collected at the LSU scale for the period from 1960 to 2006 (*Materials and Methods*).

Results and Discussion

The model simulated the SOC changes for a long-term experiment in the loam region reasonably well (Fig. S1), predicting a slight decrease for the residue removal treatment (slope, −0.074 Mg C ha^{-1} y^{-1} ; r^2, 0.83; rmsd, 2.91 Mg C ha^{-1}), a slight increase for the treatment where residues were plowed in and a green manure was applied every 4 y (slope, 0.058 Mg C ha^{-1} y^{-1} ; r^2, 0.40; rmsd, 2.37 Mg C ha^{-1}), and a somewhat greater increase for the treatment where residues were removed and 40 tons of farmyard manure was applied every 4 y (slope, 0.17 Mg C ha^{-1} y^{-1} ; r^2, 0.88; rmsd, 3.01 Mg C ha^{-1}).

For the regional scale analyses, we did a two-stage simulation. The model was initially run starting with the mean SOC stock in 1960 for each LSU and using the mean crop carbon input and manure estimates, as well as climate and soil characteristics, for each agricultural region (*SI Text*). A significant ($P < 0.05$) but weak relationship was obtained between the observed SOC changes (1960–2006) and the model predictions ($r^2 = 0.337$; Fig. S2). The main outliers in the initial simulation included the areas in which the largest changes in SOC occurred (10) (Table 1), indicating that other factors apart from the C input from crops and manure needed to be taken into account. The RothC model

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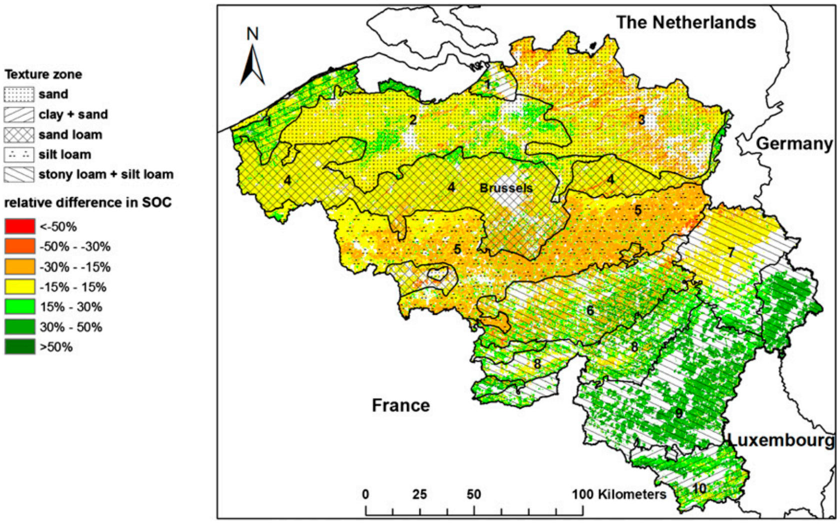

Fig. 1. Dominant soil texture and agricultural regions superimposed on relative differences in SOC stocks (1960–2006) (10). Agricultural regions: polders (Po; 1), sand region (Sa; 2), Campine (Ca; 3), sand loam region (Sl; 4), loam region (Lo; 5), Condroz (Co; 6). Herbagière Liège region (Hl; 7), Famenne (Fa; 8), Ardennes (Ar; 9), and Jura (Ju; 10).

underpredicted the SOC decrease in the cropland of the center and the north of the country (Campine, sand loam, and loam regions) and in the grasslands of the Polder, Campine, and loam regions (Fig. 1). The model also underpredicted the SOC increases in grasslands in the southeastern part of the country.

According to the Belgian soil map compiled in the 1960s and 1970s, the minimum depth to groundwater was less than 40 cm in many grassland soils in the northern part of the country (i.e., Campine, Polder, and loam region; Table 1). However, the drainage of most of these soils has considerably improved in recent decades, as 30% of the soil profiles sampled in the Polders and 50% in the Campine are situated in areas where land consolidation included improving drainage (*SI Text* and Fig. S3). It is likely that even a greater percentage of the soils have been artificially drained, but this is difficult to establish as the drainage classes of the soil map are in the process of being updated. The poorly drained soils in the polder, Campine, and loam region (average high groundwater table, 0.31–0.47 m below the surface) are all characterized by an SOC stock of more than 100 Mg C ha^{-1} (Table 1). We simulated the effect of artificial drainage of these poorly drained soils by introducing a rate modifying factor in the RothC model. These factors were derived by running the model from 1800 onward with the crop carbon and manure input dating from before agricultural mechanization (before 1960), and adjusting the modifying factors (0.81–0.97) to obtain a stable SOC stock at the level observed in 1960 for the poorly drained

Table 1. Characteristics of the outliers in SOC changes

							FYM input, Mg C/ha/y[§]		
Region/texture	Land use	n	HGW, m*	Cons, %[†]	SOC60, Mg C/ha[‡]	Δ, Mg C/ha[‡]	1958	1990	2004
Polder									
Heavy clay	Crop	5	0.52	60	72.98	14.91	1.38	2.29	1.50
Heavy clay	Grass	3	0.43	33	131.78	−38.99	1.38	2.29	1.50
Campine									
Sand	Crop	4	0.56	25	98.08	−25.94	1.51	4.62	1.50
Sand	Grass	24	0.37	46	107.74	−35.60	1.51	4.62	1.50
Sand loam									
Silt loam	Crop	56	1.30	4	55.61	−5.60	1.33	2.77	1.50
Loam									
Silt loam	Crop	110	1.18	1	63.29	−13.72	1.05	1.05	1.07
Silt loam	Grass	28	0.31	—	145.28	−54.93	1.05	1.05	1.07
Condroz									
Stony loam	Grass	13	1.30	—	69.33	21.96	1.07	0.96	0.99
Famenne									
Stony loam	Grass	27	1.24	—	80.40	17.84	1.15	1.28	1.39
Ardennes									
Stony loam	Grass	33	1.13	—	104.18	16.01	1.25	1.72	1.79

*HGW represents average highest groundwater level in cm below the surface as indicated on the Belgian soil map.

[†] Consolidation represents the percentage of the soil profiles where drainage has been improved in Flanders (VLM) (22).

[‡] SOC60 and Δ are observed initial SOC stock in 1960 (SOC60) and change in SOC stock from 1960 to 2006 (Δ).

[§] Manure (FYM) input applies to grassland and cropland in a specific agricultural region.

grasslands (Fig. S4). After drainage, the modifying factors were increased (1.33–1.40; *SI Text*) to simulate the increased decomposition of high organic matter soils. Taking into account artificial drainage, RothC predicted losses of 25 to 40 Mg C ha^{-1} for these grassland soils.

Historic land use in Belgium has been well documented based on early land use maps dating back to 1775 (15). Although broad patterns of land use have been relatively stable in most of the country from at least the medieval period, important changes in land use and management have occurred in the early 20th century, particularly in marginal areas with poor sandy soils in the northeast (e.g., Campine) and on the shallow stony soils with a wet and cold climate in the southeast (e.g., Ardennes).

It was established from the first topographical maps (15) that at least 75% of the sampled cropland soil profiles in the Campine have been under cropland since 1775. These so-called plaggen soils received very high organic inputs from manure and heath sods. Inputs of 5.2 Mg C ha^{-1} y^{-1} were reported for similar systems in the neighboring part of The Netherlands (16). The plaggen management stopped in the late 19th century when chemical fertilizers became available (16, 17). Subsistence farming on very small farms, whereby farmers tended to concentrate their manure on a limited cropland area, continued until large-scale land consolidation schemes were implemented (1956–1972; *SI Text*). To represent the effects of these historic high carbon inputs, the RothC model was run with the high organic matter input (5.2 Mg C ha^{-1} y^{-1}) from 1500 onward until land consolidation (1956–1972), after which the model was run with contemporary carbon inputs. The predicted SOC loss of croplands in the Campine reached 11.4 Mg C ha^{-1} (Fig. S5).

Land use change in the early 20th century in the Ardennes resulted in a conversion of 75% of the cropland into grassland (18). These conversions can be explained by an increase in the accessibility of the region that allowed import of food and fertilizer, leading to a specialization in extensive livestock breeding in this marginal area (19). When we accounted for this pre-1960 land use change, RothC simulated an average gain of 12 Mg C ha^{-1} as a result of the legacy of conversion of marginal croplands into grassland between 1923 and 1953 (Fig. S6).

Some significant changes were not explained, such as the SOC increase in grasslands in the Condroz, the increase in clay soils of croplands in the Polders, and the decrease in the croplands of the sand loam and loam region (Fig. 1). The Polder region borders the sand region in the north, which has a much higher manure production (Table S1). The carbon input was calculated from the production in each agricultural region as data on the spreading of manure were not available. One can assume that the actual manure input in the Polders will therefore be underestimated, and that the increase in SOC stock in the Polders can be attributed to the high manure input. The decrease since 1960 (averaging 22%) in cropland SOC in the loam region contrasts with the very small losses and gains observed in the long-term experiments in this region, which were well represented by the model (as detailed earlier). The change in vertical SOC distribution between 1960 and 2006 indicates that SOC is lost from the top 30 cm as the plow depth increased by 8 cm (20). Furthermore, erosion was estimated to remove 7.5 cm of the topsoil in this period (6). Hence, the plow layer moved deeper into the soil profile diluting the SOC content of the topsoil. Approximately half the loss in SOC stock can be attributed to erosion (6), but landscape scale studies are required to refine this estimate.

To evaluate the potential influence of climate trends during the inventory period from 1960 to 2006, we repeated the simulations with the use of the previous mean monthly climate (1930–1960). There were no significant effects on SOC dynamics compared with the results using actual observed climate (Fig. 2). Taking into account the input of crop carbon, manure, legacy land use effects, and drainage for each LSU (if applicable), the model accounted for more than 70% of the observed changes in SOC since 1960 with an rmsd of 11.72 Mg C ha^{-1} ($r^2 = 0.72$; $P < 0.01$; Fig. 2). The slope of the modeled versus observed SOC changes for each LSU is not significantly different from unity (1.28 ± 0.36) and the intercept is zero (−1.69 ± 4.95). The largest losses (11 to >45 Mg C ha^{-1}) were caused by the drainage of grassland soils after land consolidation and the abandonment of the plaggen system in the Campine (Fig. 3). The largest gains in croplands were in the sand region (9.8 Mg C ha^{-1}) where the manure input has increased by threefold up to 1990 (Table 1). The SOC increases in grassland were concentrated in the southeast and could neither be explained by plant carbon nor by manure input. At least in the Ardennes, the increases (12 Mg C ha^{-1}) were to a large extent the legacy of conversion from cropland in the period from 1923 to 1953. Overall, land consolidation and historic land conversions explained the largest losses and gains. Such interventions are often not taken into

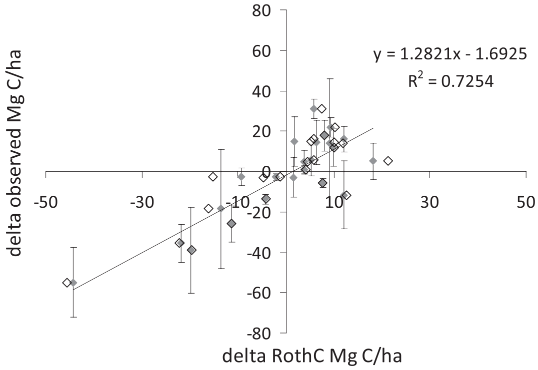

Fig. 2. Modeled SOC changes (1960–2006) for each LSU as a function of observed changes after taking drainage and land use legacy effects into account using the monthly climate data for 1960 to 2006 (closed symbols) and the average monthly data for the 1930 to 1960 period (open symbols). The SEs of the observed changes are indicated.

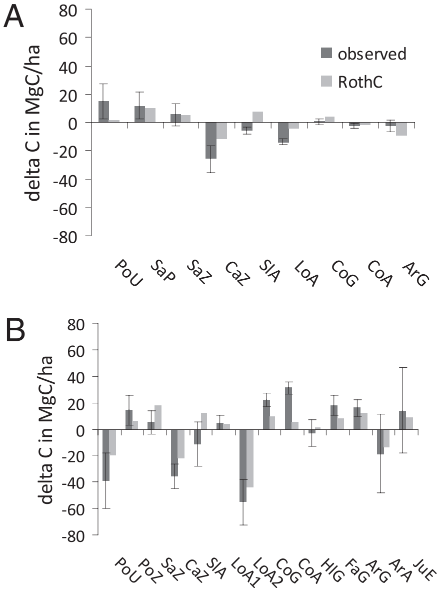

Fig. 3. Modeled and observed SOC changes (1960–2006) for each LSU in croplands (*A*) and grasslands (*B*) with SEs of observed changes. Details of the LSUs are given in Table 1 and location of the agricultural regions in Fig. 1. The following texture symbols were used: U, heavy clay; P, sandy loam; Z, sand; A, silt loam, G, stony loam; and E, clay. LoA1 indicate well to moderately drained soils and LoA2 the poorly drained soils in the loam region.

account when process-based models are run at a regional scale (21). The episodic nature of such interventions explains part of the differences in the results of repeated SOC inventories and also the differences between such inventories and regional SOC models. These results demonstrate that SOC monitoring networks can be used both to verify the reliability of process-based model runs at the regional scale and to detect the driving forces of the observed SOC trends. Hence, SOC monitoring networks complement long-term experiments by covering the full range of climate, soil, and management combinations within a country.

Materials and Methods

Spatial Aggregation of the Data. Climate, plant input, and manure data were averaged for agricultural regions with broadly similar soil type, climate, and agricultural management (Fig. 1). These regions were then overlaid on the soil series with similar texture class. Within these units, input data and the model results were averaged for cropland and grassland, respectively. This created so-called LSUs that were series of discontinuous polygons.

Soil Data. Changes in SOC stock were derived from resampling of a soil database compiled during the national soil survey from 1950 to 1970 (22). Only soil profiles that remained in the same land use during the period from 1960 to 2006, as verified on a sequence of topographical maps and aerial photographs, were resampled from 2004 to 2007. A stratification according to land use, soil texture, drainage, and agricultural region was used to achieve a high enough sample density to detect significant changes in a large number of LSUs (6) and to cover the range of land use, texture, and drainage combinations (10). In total, 629 soil profiles over the entire country were resampled. The SOC content in both the historic and current sampling campaign was determined using the classic dichromate method of Walkley and Black (23), and a correction factor of 1.33 was used to account for incomplete oxidation. The SOC stock is calculated for both dates by multiplying the SOC content of the first 30 cm by the bulk density while correcting for rock fragment content. We used a pedotransfer function (24) to estimate the bulk density based on the observed SOC concentration. Clay percentage and highest groundwater table were derived from the soil map for each LSU (10) (Table S1).

Carbon Input from Crops and Manure. The weighted average annual crop carbon input for an agricultural region was estimated from the crop carbon input of the individual crops multiplied by the area grown as declared in the agricultural census (*SI Text*). The contemporary crop carbon input for the different crops was compiled from local data sources (Table S2). The historic crop carbon input was based on the historic crop yields from the FAOstat database (http://faostat.org/). Historic yields were then converted to crop carbon input by means of the linear regression developed by Franko (13).

$$\mathrm{C_{(t)} = K + FAO_{(t)} \times F}, \qquad [1]$$

where $C_{(t)}$ is the C in residues (aboveground plus roots) in dt (i.e., 100 kg) C ha^{-1} for year *t*, $FAO_{(t)}$ is the crop yield in fresh matter as given in the FAOstat database in dt fresh matter ha^{-1} for year *t* and K and F are constants. We used K values of 4.0 (in dt C ha^{-1}) for cereals, 0.8 for potatoes, and 1.6 for sugar beets, and F values of 0.08 for cereals, 0.016 for potatoes, and 0.008 for sugar beet (*SI Text* shows the sensitivity of the model runs to these parameters). As the carbon inputs for 2006 (Eq. **1**) were considerably lower than the ones calculated from local data sources (Table S2), a correction factor (i.e., reported C input for 2006 divided by the calculated C input from Eq. 1 was used). The K and F values of sugar beet were also used for chicory and fodder beet, and the ones for cereals for maize and dry beans. Flax and rapeseed carbon input were considered constant, as no parameters were available for these crops. Temporary grassland (i.e., leys, grass seed, and leguminous fodder crops) were considered to increase their carbon input by 0.5% per year (25). These inputs do not include rhizodeposition and assume that straw is removed for animal bedding. To account for these inputs, the cereal inputs were multiplied by 1.5 and the potato and sugar beet inputs by 1.35 (26). No country-specific data for permanent grasslands were available, and the change in carbon input over the years was estimated to be low for grasslands throughout Europe (0.25% per year) (25). As a result of the lack of data, a constant carbon input of 2.92 Mg C ha^{-1} y^{-1} was assumed for the top 30 cm of the soil (27).

Carbon input from manure was derived from the livestock number in each category multiplied by their average manure production and the time spent in the stables (28). For 2006, the manure produced exceeded the maximum manure N input restricted at 170 kg N ha^{-1} or, depending on the C/N ratio of the manure, an equivalent of 1.5 Mg C ha^{-1}. We linearly reduced the carbon input from manure across all the soils starting in 1991 to reach the 2006 limits.

Climate Data. The monthly precipitation and temperature was extracted from the CRU TS 1.2 gridded database (29) at a resolution of 10 minutes. Most of the model runs were carried out with the monthly data for each year from 1960 to 2006, but for some spin-up runs on the effect of historic land use change and drainage, long-term averages (1900–1960) were used. Monthly potential evapotranspiration was calculated from the temperature using the Thornthwaite equation (30).

Rothamsted Carbon Model. We used the RothC 26.3 model (12) that partitions soil organic matter into different pools: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), humified organic matter (HUM), and CO_2. The decay of each pool has a first -order kinetic and the default decomposition rates (y^{-1}) are used: 10.0 (DPM), 0.3 (RPM), 0.66 (BIO), and 0.02 (HUM). Part of the total SOC (in Mg C ha^{-1}) is attributed to the inert organic matter pool (IOM in Mg C ha^{-1}) (31) as follows:

$$\mathrm{IOM} = 0.049\ \mathrm{SOC}^{1.139} \qquad [2]$$

The model includes rate modifying factors of the first-order kinetics for temperature, moisture, and soil cover/tillage. A rate modifying factor for anaerobic conditions and rapid decomposition of formerly anaerobic soils upon drainage was added (*SI Text*). Plant carbon input occurred from April to September with a peak in July, and manure carbon input was applied in February and October. The grassland soils were treated in the model as "covered" (having some portion of a plant canopy over the soil) all year round, whereas croplands were covered from March until September. RothC was initialized on the SOC data from 1960, using a fixed distribution over the pools after the IOM was subtracted: 1% DPM, 15.5% RPM, 1.5% BIO, and 82% HUM. Sensitivity analysis of RothC under Flemish cropland conditions showed that this represented a management history of croplands receiving a moderate FYM application (*SI Text* includes a discussion on the sensitivity of the model runs to the initial pool distribution).

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1. Smith P, et al. (2007) Agriculture. *Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change 2007*, eds Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (Cambridge Univ Press, Cambridge, UK), Chapter 8.
2. Saby NPA, et al. (2008) Will European soil monitoring networks be able to detect changes in topsoil organic carbon content? *Glob Change Biol* 14:2432–2442.
3. Smith P, et al. (2007) Climate change cannot entirely be responsible for soil carbon losses in England and Wales, 1978-2003. *Glob Change Biol* 13:2605–2609.
4. Bellamy PH, Loveland PJ, Bradley RI, Lark RM, Kirk GJD (2005) Carbon losses from all soils across England and Wales 1978-2003. *Nature* 437:245–248.
5. Sleutel S, et al. (2003) Carbon stock changes and carbon sequestration potential of Flemish cropland soils. *Glob Change Biol* 9:1193–1203.
6. Goidts E, van Wesemael B (2007) Regional assessment of the changes in soil organic carbon changes under agriculture in Southern Belgium (1955-2005). *Geoderma* 141: 341–354.
7. Liao Q, et al. (2009) Increase in soil organic carbon stock over the last two decades in China's Jiangsu Province. *Glob Change Biol* 15:861–875.
8. Ogle SM, Paustian K (2005) Soil carbon as an indicator of environmental quality at the national scale: Inventory monitoring methods and policy relevance. *Can J Soil Sci* 85: 531–540.
9. Milne E, et al. (2007) National and sub-national assessments of soil organic carbon stocks and changes: The GEFSOC modelling system. *Agric Ecosyst Environ* 122:3–12.
10. Meersmans J, et al. (2010) Spatial analysis of soil organic carbon evolution in Belgian croplands and grasslands, 1960-2006. *Glob Change Biol*, 10.1111/j.1365-2486.2010.02183.x.

11. Goidts E, van Wesemael B, Van Oost K (2009) Driving forces of soil organic carbon evolution at the landscape and regional scale using data from a stratified soil monitoring. *Glob Change Biol* 15:2981–3000.
12. Coleman K, Jenkinson DS (1999) *RothC-26.3. A Model for the Turnover of Carbon in Soils.* (Lawes Agricultural Trust, Hertfordshire, UK).
13. Ludwig B, Schulz E, Rethemeyer J, Merbach I, Flessa H (2007) Predictive modelling of C dynamics in the long-term fertilization experiment at Bad Lauchstädt with the Rothamsted carbon model. *Eur J Soil Sci* 58:1155–1163.
14. Leifeld J, Reiser R, Oberholzer HR (2009) Consequences of conventional versus organic farming on soil carbon: Results from a 27-year field experiment. *Agron J* 101: 1204–1218.
15. Anonymous (1965) *Carte de Cabinet des Pays-Bas Autrichiens Levée à l'Initiative du Comte Ferraris.* (Brussels, Pro Civitate).
16. Schulp CJE, Verburg PH (2009) Effect of land use history and site factors on spatial variation of soil organic carbon across a physiographic region. *Agric Ecosyst Environ* 133:86–97.
17. Blume HP, Leinweber P (2004) Plaggen soils: Landscape history, properties and classification. *J Plant Nutr Soil Sci* 167:319–327.
18. Stevens A, van Wesemael B (2008) Soil organic carbon stock in the Belgian Ardennes as affected by afforestation and deforestation from 1868 to 2005. *For Ecol Manage* 256:1527–1539.
19. Petit CC, Lambin EF (2002) Long-term land-cover changes in the Belgian Ardennes (1775-1929): Model-based reconstruction vs. historical maps. *Glob Change Biol* 8: 616–630.
20. Meersmans J, et al. (2009) Changes in organic carbon distribution with depth in agricultural soils in northern Belgium, 1960-1990. *Glob Change Biol* 15:2739–2750.
21. Ciais P, et al. (2010) The European carbon balance. Part 2: Croplands. *Glob Change Biol* 16:1409–1428.
22. Van Orshoven J, Maes J, Vereecken H, Feyen J, Dudal R (1988) A structured database of Belgian soil profile data. *Pedologie (Gent)* 38:191–206.
23. Walkley A, Black IA (1934) An examination of the Degtjareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci* 37:29–37.
24. Manrique LA, Jones CA (1991) Bulk density of soils in relation to soil physical and chemical properties. *Soil Sci Soc Am J* 55:476–481.
25. Smit HJ, Metzger MJ, Ewert F (2008) Spatial distribution of grassland productivity and land use in Europe. *Agric Syst* 98:208–219.
26. Kuzyakov Y, Domanski G (2000) Carbon input by plants into the soil. Review. *J Plant Nutr Soil Sci* 163:421–431.
27. Coleman K, et al. (1997) Simulating trends in soil organic carbon in long-term experiments using RothC-26.3. *Geoderma* 81:29–44.
28. Dendoncker N, van Wesemael B, Rounsevell MDA, Roelandt C, Lettens S (2004) Belgium's CO_2 mitigation potential under improved cropland management. *Agric Ecosyst Environ* 103:101–116.
29. Mitchell TD, Carter TR, Jones PD, Hulme M, New M (2004) *A Comprehensive Set of High-Resolution Grids of Monthly Climate for Europe and the Globe: The Observed Record (1901-2000) and 16 Scenarios (2001-2010). Working Paper 55.* (Tyndall Centre for Climate Change Research, Norwich, UK).
30. Shaw EM (1994) *Hydrology in Practice* (Chapman & Hall, London), 3rd Ed.
31. Falloon P, Smith P, Coleman K, Marshall S (1998) Estimating the size of the inert organic matter pool from total soil organic carbon content for use in the Rothamsted carbon model. *Soil Biol Biochem* 30:1207–1211.