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Biotechnol. Agron. Soc. Environ. 2004 **8** (2), 141–146

The inventory-based approach for prediction of SOC change following land use change

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This paper describes and illustrates an approach to predict soil organic carbon (SOC) change in time after land use change as derived from SOC differences in space. The approach requires the availability of a SOC inventory for spatially explicit combinations of soil and land use type, further termed landscape units (LSU). SOC of LSU with equal soil type but different land use type are compared and the observed differences in SOC are interpreted as the expected SOC change after the corresponding land use change. From a confrontation with time series of agro-statistical data on crop and grassland areas and on animal manure production, we conclude that the approach is a low-cost alternative for more complex methods like multi-temporal assessments and modelling, provided that (i) an inventory reflecting current management and climate conditions and (ii) additional information on the extent and type of recent land use changes are available. Examples of land use and land management changes are discussed, such as grassland – cropland conversions, the conversion of permanent to temporary grassland, or changes in manure application.
Keywords. Soil organic carbon, national inventory, spatially explicit landscape units, Belgium.

Quantification des impacts du changement d'affectation des terres sur les stocks de carbone organique des sols sur base de l'interprétation de différents inventaires pédologiques. Cet article décrit et illustre une méthode pour prédire le changement temporel du stock de carbone organique dans le sol (COS) résultant d'un changement d'affectation des terres sur base des différences observées dans l'espace. La méthode repose sur l'inventaire des teneurs en COS pour différentes combinaisons de sols et d'affectation des terres, appelées "unités paysagères". Les différences dans les teneurs en COS pour des unités paysagères, sur un même type de sol soumis à diverses affectations des terres, sont interprétées par rapport au changement d'affectation des terres. Nous concluons d'une analyse de séries temporelles des statistiques agricoles sur les cultures, les herbages et les effluents d'élevages, que cette méthode est une alternative peu coûteuse à des méthodes plus complexes telles que les estimations multi-temporelles et la modélisation. Notre méthode présuppose toutefois (i) un inventaire représentatif des conditions actuelles de gestion des terres et du climat et (ii) des données statistiques récentes sur l'importance et les types de changement d'affectation des terres. Nous discutons des exemples de gestion des terres et de changement d'affectation des terres comme la conversion de pâtures en terres de culture et celle de prairies permanentes en prairies temporaires, et enfin l'apport d'effluents d'élevage.
Mots-clés. Carbone organique du sol, inventaire national, unité paysagère, Belgique.

1. INTRODUCTION

The impact of land use change on the soil organic carbon (SOC) content depends on a number of factors, such as the old and new land use type, the soil type, management and climate. To assess this impact, the need arises to quantify (i) typical SOC change values for the considered land use change and (ii) the area to which the change is applicable. Different strategies are possible to address these two issues.

Typical change values can be estimated by specific studies, for example time series analysis. The measurement of SOC values at time lags after land use change allows the reconstruction of SOC evolution (Van Meirvenne *et al.*, 1996; Post, Kwon, 2000; Guo, Gifford, 2002). Nevertheless, this type of multi-temporal chronosequence is time-consuming, rare and its validity often limited to the local conditions. A second option is the uni-temporal chronosequence, where analysis in time is mimicked by analysis in space (Kirschbaum *et al.*, 2001; Eve *et al.*, 2002; Tate *et al.*, 2003; Wu *et al.*, 2003). In this approach, it is assumed that the SOC after land use change can be predicted based on uni-temporal SOC stocks in the soil with the original land use type on the one hand and future land use type on the other hand. This approach can be based on a one-time and large-scale inventory effort. A third approach is the mechanistic or process-based modelling approach, for which the previously mentioned uni- and multi-temporal studies can provide calibration and validation data (Falloon *et al.*, 2002; Vleeshouwers, Verhagen, 2002; Nabuurs *et al.*, 2003).

The prediction of the area to which the land use change is applicable can be based on global change scenario modelling or on the extrapolation of land use statistics in a trend analysis (Vleeshouwers, Verhagen, 2002).

The present study investigates the validity of a uni-temporal prediction of SOC change after land use change. The concept is applied to the territory of Belgium for which three independent and consecutive inventories are considered. Estimating the area to which changes are applicable is beyond the scope of the present study. An *ad hoc* scenario is applied to illustrate the possibilities of the methodology.

2. MATERIALAND METHODS

2.1. Belgian soil inventories

This paper considers three SOC inventories for the country Belgium, namely for the years 1960, 1990 and 2000. The basic spatial unit is the landscape unit, a collection of polygons with unique soil and land use characteristics, derived from a map overlay of the 1990 CORINE Land Cover map (CLC) and the Belgian Soil association map (Lettens *et al.*, 2004). The 34 CLC land cover types are regrouped into 6 land use types: cropland, grassland, broadleaf forest, coniferous forest, mixed forest and built up. According to the Soil association map, 64 soil associations occur in Belgium, grouping soils with similar texture, profile development and drainage status.

The 1960 inventory is described extensively in Lettens *et al.* (2004). It is based upon a detailed database with 13,033 profile analyses representing 69,600 horizons, including soil series, map coordinates and land use class (Van Orshoven *et al.*, 1993). For each horizon, depth and thickness, textural fractions and class, volume percentage of rock fragments, organic carbon content (percentage C by mass, measured according to Walkley and Black (1934)) and inorganic carbon content (weight percentage $CaCO_3$ determined by titration, De Leenheer *et al.* (1960)) are available to a depth of 120 cm. Calculating the SOC (t C ha^{-1}) of the horizons of each profile is possible by multiplying the carbon content, the estimated bulk density and the non stony volume of soil. The SOC of an LSU is the average SOC for a specified depth of a selection of soil profiles typical of this LSU. Profiles are typical for an LSU if they are either situated inside the LSU ("geomatching"), or if they have similar land use and soil type as the LSU ("classmatching"). For each LSU, the best estimate is selected, based upon the number of selected profiles and, for classmatching, the degree of similarity between land use and soil type. In case of multiple matching profiles, measures of spread can be computed per LSU.

The 1990 and 2000 inventories are of the same type, but computation methodology differs from the 1960 inventory. It is based upon a number of scattered soil inventories, carried out by different instances for different purposes. The databases are heterogeneous with respect to the degree and standard of aggregation (SOC of individual profiles or average SOC of a number of profiles), the SOC measurement techniques, the geographic extent and the depth interval interpretation (soil horizon *versus* fixed depth). Most databases contain an average SOC content for a limited depth per land use type, municipality, year, administrative region and, sometimes, agropedological region (i.e. 14 broad zones within Belgium reflecting dominant soil texture and climate). The number of observations and the standard deviation are known. The SOC averages and standard deviations are disaggregated to estimate the SOC content of landscape units. Standard deviation is updated constantly during this exercise. No forest soil inventory exists for 1990, therefore the 1990 inventory is limited to the two agricultural land use types grassland and cropland.

2.2. Prediction of SOC change after land use change

With the available inventories, it is evidently possible to assess past SOC changes of LSU. Moreover, using data of one of the inventories and comparing two LSU that consist of an identical soil type but a different land use type could predict future SOC change following land use change (LUC). The two different land use types are then assumed to represent the original and future land use type of the considered LUC. The difference in SOC content between the two LSU is an estimation of the expected SOC change after LUC only if both LSU are characterized by equilibrium

SOC content. This means that SOC remains stable when land use, land management and environmental properties (such as climate, CO_2 concentration or nitrogen deposition) do not change either. Two questions need to be investigated before applying this approach. Is it correct to assume that the SOC content of the LSU, as estimated by the inventories, is in balance ? And, which inventory should be preferred for the estimation, the most recent or the most detailed one ?

3. RESULTS AND DISCUSSION

3.1. Choosing the optimal inventory

It is clear that the 1960 inventory is based on the most detailed data. However, does this necessarily mean that the 1960 inventory is the most suited to use for the estimation of SOC change after land use change in the beginning of the 21st century ? When considering SOC by land use type in Belgium, all land use types have gained carbon between 1960 and 1990–2000. The agricultural land use types have both lost carbon between 1990 and 2000. This seems to suggest that external factors influencing SOC between 1960 and 2000 (such as management, climate change or nitrogen deposition) had a similar influence on all land use types. This would mean that the influence of these factors on temporal SOC changes is minimal and that the 1960 inventory is preferable, due to its more detailed base data. However, when looking closer at individual landscape units, it becomes clear that SOC changes differ considerably throughout the country. An important distinction occurs between the agropedological zones (**Table 1**). The increase in SOC between 1960 and 1990 is more pronounced in Flemish agropedological zones (for example Kempen in **Table 1**) than it is in Walloon zones (such as Condroz and Ardenne in **Table 1**). In some Walloon LSU a SOC decrease is observed. This can be due to a number of management factors. From animal statistics (NIS, 2000) can be derived that the application of farmyard manure (FYM) in Wallonia is lower than in Flanders and has not changed considerably since 1960, or has in some cases even decreased slightly. The area is hillier in Wallonia than in Flanders, thus erosion may have played a part in the SOC losses of cropland. **Table 1** shows the estimated amount of manure that is applied on agricultural land in the Kempen, with a strong increase in manure application, and the Condroz, with a small decrease in manure application. Farmyard manure and slurry production were calculated according to the methodology proposed by Dendoncker *et al.* (2004). These authors estimate the annual production of FYM and slurry using the livestock in age classes, the type of housing, the time spent in the housing and excretion coefficients published by the Walloon Government (AGW, 2002). Farmyard manure and slurry inputs are then converted to carbon stocks using a dry matter content of 25 % for FYM, 12 % for slurry (Vlaamse Landmaatschappij, 2004) and a carbon content of 41 % for both (Brady, Weil, 1996). Since no data are available for Belgium, it is assumed that FYM and slurry produced within a region were spread evenly on arable and grassland soils within the same region (van Wesemael *et al.*, 2004).

If the FYM data are compared with the SOC contents of the LSU that typically occur within each agropedological zone, a trend is visible. Between 1960 and 1990, the strong increase in manure application coincides with a rise in SOC content in the LSU of the Kempen. A stabilization of the manure application from 1990 onwards corresponds with a slight decrease in SOC content. In the Condroz application of manure did not change dramatically and SOC contents also remained stable. Due to the impact of management on SOC content of LSU and the regional variations of management, the use of the most recent inventory available appears preferable. Hence, the 2000 inventory is preferred to the 1960 and 1990 inventories for the uni-temporal estimation of SOC changes after land use change on a soil association.

When considering the difference in SOC content of LSU on an equal soil type with a different land use type, the impact of land use change can be quantified based upon the 2000 inventory. An example is shown in **figure 1** for the associations 15 and 52, associations that cover large areas in the pedological zones Kempen and Ardenne respectively.

If an *ad hoc* land use change scenario is considered that converts all grassland of association 52 into coniferous forest, an increase of 49 t C ha^{-1} would be realised. Since association 52 contains 15,720 ha grassland, this would mean a total extra SOC storage of 0.8 Mt C.

3.2. Equilibrium state of SOC of LSU

In the proposed approach, other factors than the management related ones could play a role. Recent land use changes (Janssens *et al.*, 2003) are not recorded during sampling but could influence average SOC content of LSU. After a recent conversion of a SOC-rich land use type (e.g. grassland) towards a SOC-poor land use type (e.g. cropland), the decrease in SOC will follow quickly and the effect on the average SOC content of the cropland will tend to be small. However, if the opposite is true, e.g. when converting cropland to grassland, the increase in SOC is slow, and inclusion of the recently converted grassland in the soil survey will lower the average SOC content of grassland (Post, Kwon, 2000).

Table 1. Amount of C applied to agricultural land as farmyard manure (FYM) or slurry (t C ha^{-1}) in three agropedological regions between 1958 and 2002 and the SOC content (t C ha^{-1}) of a selection of LSU within the agropedological regions. LSU are presented as the combination of two numbers, the association number – the land use type — *Quantités de carbone organique épandues sur les terres agricoles sous forme de fumier (FYM) ou de lisier dans trois zones agricoles sélectionnées, entre 1958 et 2002, et teneurs en carbone organique du sol (SOC) au sein de ces trois zones. Les unités paysagères (LSU) sont présentées sous forme de combinaisons de deux nombres, l'un représentant l'association pédologique, l'autre l'occupation du sol.*
Association 14 = dry sand to loamy-sand soils with humus and/or ferralic B horizon — *sols sableux à sablo-limoneux secs avec un horizon B humique ou ferrique* ;
association 15 = wet sand to loamy-sand soils with humus and/or ferralic B horizon — *sols sableux à sablo-limoneux humides avec un horizon B humique et/ou ferrique* ;
association 17 = wet sand to light sandloam soils with colour B horizon or with texture B horizon — *sols sableux à sablo-limoneux humides légers à horizon B de couleur ou à horizon B textural* ;
association 42 = stony loam soils with texture B horizon or structure B horizon with admixture of shale & sandstone — *sols limono-caillouteux à horizon B textural ou à horizon B structural, à charge de schiste et grès* ;
association 43 = stony loam soils with texture B horizon or structure B horizon with admixture of sandstone — *sols limono-caillouteux à horizon B textural ou à horizon B structural, à charge de psammite* ;
association 44 = stony loam soils with texture B horizon or structure B horizon with admixture of limestone — *sols limono-caillouteux à horizon B textural ou à horizon B structural, à charge de calcaire* ;
association 50 = stony loam soils with structure B horizon with admixture of shale and slate — *sols limono-caillouteux à horizon B structural à charge de schiste et phyllade* ;
association 51 = stony loam soils with structure B horizon with admixture of shale and sandstone — *sols limono-caillouteux à horizon B structural à charge de schiste et grès* ;
association 52 = dry slightly stony loam soils with structure B horizon— *sols secs limoneux peu caillouteux à horizon B structural* ;
land use type 3 = grassland — *occupation du sol 3 = prairie* ; land use type 4 = cropland— *occupation du sol 4 = terre arable.*

Year	Kempen					Condroz					Ardenne				
FYM & slurry (t C ha^{-1})															
1958	1,51					1,07					1,25				
1970	2,78					1,15					1,47				
1990	4,62					0,96					1,72				
2002	4,07					0,99					1,79				
SOC (t C ha^{-1}) in LSU															
	15-4	**15-3**	**17-4**	**14-4**	**17-3**	**44-4**	**43-4**	**42-4**	**44-3**	**43-3**	**50-4**	**50-3**	**52-4**	**52-3**	**51-4**
1960	51	55	40	45	47	36	34	35	50	36	53	58	54	61	50
1990	61	81	55	59	80	34	30	30	64	56	47	64	50	59	43
2000	57	73	50	55	73	34	32	33	59	54	52	60	55	60	47

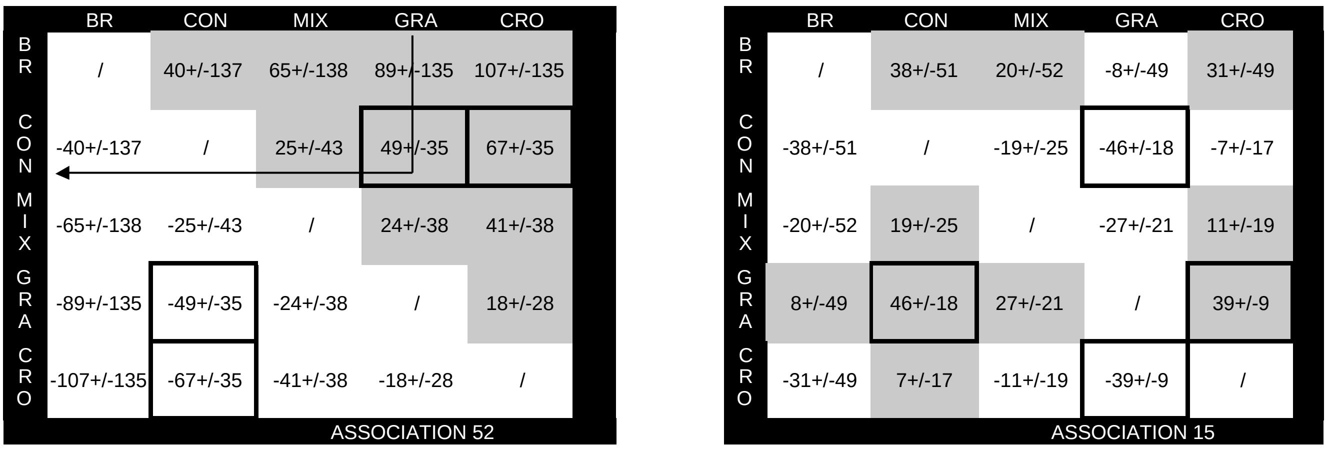

Figure 1. SOC change +/- 95% confidence intervals (t C ha^{-1}) following land use change, based upon the 2000 inventory for associations 52 and 15. Increases in SOC are in grey and significant changes are within black squares. The matrix must be read in the direction of the black arrow — *Changements des teneurs en carbone organique du sol (SOC) +/- intervalle de confiance à 95% (t C ha^{-1}) suite à la modification d'occupation du sol, calculés sur base de l'inventaire de 2000 pour les associations de sol 52 et 15. Les augmentations sont indiquées en gris et les changements significatifs sont encadrés en noir. La matrice doit être lue dans la direction de la flèche noire.* BR = broadleaf forest — *forêt feuillue* ; CON = coniferous forest — *forêt résineuse* ; MIX = mixed forest — *forêt mixte* ; GRA= grassland — *prairies* ; CRO = cropland — *terre arable.*

The NIS (2000) supplies statistics of the area of different agricultural land use types. The data allow the assessment of net changes, but it remains problematic to estimate the extent of gross changes. The data given in **table 2** show that the area under cropland in the Condroz increased steadily between 1960 and 2000 (2–5% per year), while the area under grassland decreased with 1–5% per year. The total area under agriculture decreased slightly by approximately 0.2% per year. Such land use change could result in overestimated SOC stocks in cropland, due to remainders of the high grassland stocks. However, the data do not reflect this phenomenon, since cropped LSU in the Condroz lost carbon during 1960–1990. In the Ardenne, arable land decreased strongly between 1960 and 1990, while grassland increased. The expected decrease in SOC content of grasslands in the same period cannot be detected in the data. A third land use change under consideration is the increase in temporary grassland at the expense of permanent grassland. In the agro-statistical database, temporary grassland is classified under cropland (**Table 2**; NIS, 2000), but during sampling, soil surveyors classified temporary grassland soil samples under the land use type grassland. Between 1990 and 2000, the conversion permanent–temporary grassland took place throughout Belgium, but was especially important in the regions Ardenne and Kempen. Grassland soils of Ardenne and Kempen did lose an important amount of SOC between 1990 and 2000, but not to a greater extent than for instance the Condroz, where the extent of temporary grassland is limited. These observations suggest that conversions between agricultural land use types do not influence SOC as strongly as changing management within a given land use type.

Table 2. Area (km^2) of land use types in the agropedological zones Kempen, Condroz and Ardenne between 1958 and 2000, according to NIS. Temporary grassland is considered as a sub-category of cropland — *Surfaces (km^2) occupées par les cultures et les prairies dans les zones agricoles de Campine, du Condroz et de l'Ardenne entre 1958 et 2000, d'après l'Institut National de Statistiques (INS). Les prairies temporaires sont considérées comme une sous-catégorie de terres de cultures.*

Year	**Area in** (km^2)		
Land use type	**Kempen**	**Condroz**	**Ardenne**
1958			
cropland	503	651	459
grassland	779	808	762
total agricultural area	1309	1483	1223
1965			
cropland	348	650	401
grassland	828	792	804
total agricultural area	1225	1470	1209
1970			
cropland	268	674	330
grassland	843	745	840
total agricultural area	1143	1451	1172
1975			
cropland	313	743	314
grassland	762	669	839
total agricultural area	1087	1417	1154
1980			
cropland	391	774	307
temporary grassland	91	11	62
permanent grassland	610	598	807
total agricultural area	1012	1375	1115
1985			
cropland	399	797	222
temporary grassland	64	10	22
permanent grassland	583	551	858
total agricultural area	993	1350	1081
1990			
cropland	475	828	159
temporary grassland	98	29	29
permanent grassland	479	515	892
total agricultural area	966	1346	1052
1995			
cropland	669	894	352
temporary grassland	166	93	236
permanent grassland	379	444	701
total agricultural area	1062	1340	1056
2000			
cropland	775	862	356
temporary grassland	218	46	245
permanent grassland	341	481	731
total agricultural area	1133	1345	1088

4. CONCLUSIONS

The feasibility of estimating SOC change after LUC based on a uni-temporal inventory depends on the availability of (i) a recent inventory that represents the current management and climate conditions and (ii) additional information on the extent and nature of recent land use changes. If land use changes occur gradually and a large number of statistically sound observations are available, the influence of recent land use changes on SOC of LSU will be small. It is important to keep in mind that agro-statistical data on land use tend to underestimate the extent of land use changes since they reflect net differences (one way) only. Data on gross (two-ways) changes are rare.

More subtle changes within a land use type, such as the conversion of permanent to temporary grassland, could have a more pertinent influence on SOC. The inclusion of temporary grassland into previously exclusively permanent grassland will continue to lower the average SOC content of the land use type grassland. This situation is therefore different from the normal recent land use changes, where the effect on average SOC disappears in time. Adequate definition of landscape units is necessary to prevent this type of error.

Acknowledgements

This research has been performed in the framework of the METAGE-project (EV/01/14). The researchers gladly acknowledge the Belgian Science Policy for their financial support.

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