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Advances in Soil Science

**GLOBAL CLIMATE
CHANGE AND
TROPICAL ECOSYSTEMS**

Edited by

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Modeling Soil Carbon Dynamics in Tropical Ecosystems

P. Smith, P. Falloon, K. Coleman, J. Smith, M.C. Piccolo, C. Cerri, M. Bernoux, D. Jenkinson, J. Ingram, J. Szabó and L. Pásztor

I. Introduction

Soil organic matter (SOM) plays a central role in nutrient availability, soil stability and in the flux of trace greenhouse gases between land surface and the atmosphere. It represents a major pool of carbon within the biosphere, estimated at between 1400×10^{15} g (Post et al., 1982) and 1500×10^{15} g (Batjes, 1996) globally, about twice that in atmospheric CO_2 and acts as both a source and a sink for carbon and nutrients.

The ability to predict the effects of climate, atmospheric composition and land-use change on SOM dynamics is essential in formulating environmental, agricultural and social / economic policies. Mathematical models encapsulate our best understanding of SOM dynamics and are essential tools for predicting the effects of environmental change, for testing specific scenarios and for developing strategies to mitigate the effects of environmental change. Changes in climate are likely to influence the rates of accumulation and decomposition of SOM through changes in temperature, moisture and the rate of return of plant residues to the soil. Other changes, especially in land use and management, may have even greater effects. Land-use change in the tropics is recognized to be of critical importance in the global carbon cycle (Schimel, 1995) since (a) SOM turnover is faster in tropical than in temperate ecosystems (Trumbore, 1993; Paustian et al., 1997b), (b) tropical ecosystems contain a large amount of carbon (Foley, 1994), and (c) land-use change is occurring rapidly in tropical regions (Dixon et al., 1994).

In this chapter, the soil carbon models participating in the Global Change and Terrestrial Ecosystems Soil Organic Matter Network (GCTE-SOMNET) are briefly reviewed. A discussion follows describing which of these have been applied to natural ecosystems and which have been evaluated for use in the tropics. The approaches used by these models are then described, with a description of the type of input data required and the type of output provided.

Many models have been used to describe and predict changes in soil carbon at the point, plot or field scale but few have been used at regional, national or continental scales. Modeling of carbon dynamics at the regional level and higher presents a number of problems, for example, how to simulate carbon turnover at depth, how to derive soil carbon inputs or estimates of net primary productivity (NPP), and how to acquire data on land-use / land-management history. These and other potential pitfalls are outlined briefly in this chapter.

Other problems arise when applying models in the tropics when they have been developed for use with nontropical climates, soils and ecosystems. These difficulties can be overcome by a full evaluation of the model using experiments from within the same region to check that the models are performing well and, if necessary, to recalibrate the models for the specific, local conditions.

Examples of the application of one soil carbon model, the Rothamsted Carbon Model (RothC), to a semi-arid agroecosystem in Syria and to a tropical Brazilian chronosequence where native forest has been cleared for pasture over the course of 23 years are provided.

In the last sections of this chapter, the application of RothC to a temperate dataset originating from Hungary is described. This application demonstrates the type of Carbon Model-Geographical Information System (GIS) linkage that will be required when modeling soil carbon dynamics at the regional level in tropical ecosystems, a strategy for which is described.

II. SOM Models Participating in SOMNET – Previous Evaluation in Tropical Ecosystems and Their Input Requirements

The Global Change and Terrestrial Ecosystems Soil Organic Matter Network (GCTE-SOMNET) is a network of SOM modellers and holders of data from long-term experiments that was established to facilitate scientific progress in predicting the effects on SOM of changes in land-use, agricultural practice and climate. Since 1995, SOMNET has attracted contributions from 29 SOM modellers and over 70 long-term experimentalists from around the world (Smith et al., 1996a, 1996b; Powlson et al., 1997; Smith et al., 1997a). Metadata (as well as a number of actual datasets) were collected from each participant; from these returns, an online database was constructed which is available for free global access at URL <http://saffron.res.bbsrc.ac.uk/cgi-bin/somnet>. The data is summarized in Smith et al. (1996a).

Twenty-four models registered with SOMNET in 1996 have recently been reviewed in detail (Molina and Smith, 1997; Smith et al., 1998a). In this chapter, the current 29 SOMNET models are examined for their input-data requirements, and to see which have previously been applied to tropical ecosystems. Table 1 lists the SOMNET models and shows the ecosystem-types and climatic regions for which each model has been evaluated.

Nine of the SOMNET models have been evaluated for use in tropical ecosystems (Table 1), i.e., CENTURY, DNDC, EPIC, McCaskill and Blair CNSP pasture model, MOTOR, RothC, SOCRATES, SOMM and Sundial. Of these, only CENTURY and RothC have so far been evaluated for grassland, forestry and arable ecosystems in the tropics.

A recent comparison of nine leading SOM models (Powlson et al., 1996; Smith et al., 1997d) was conducted in which they were evaluated against 12 long-term datasets from 7 long-term experiments in the temperate climatic region. A group of six models (RothC, CENTURY, DAISY, CANDY, NCSOIL and DNDC) performed significantly better than did three others (Smith et al., 1997e). Of these six, only two models were able to simulate all land-uses for the entire duration of each experiment (RothC and CENTURY).

Table 2 describes the data-input requirements for each model and the main soil outputs that each provide. Most models require meteorological and soil input data that are readily available, i.e., simple meteorological data on a daily or monthly timestep and simple descriptions of the soil. All models also require details of land-management and land-management history (Table 2) which are not always so easily available. The availability of good quality data in a form that can be made spatially explicit may often limit confidence in the use of SOM models at the regional level.

All of the models output changes in total carbon and many output a variety of other values (e.g., nitrogen dynamics, soil temperature and water dynamics, gaseous losses and other nutrients (Table 2). The information summarized in Tables 1 and 2 can be used to select a model for use in tropical ecosystems, depending upon the type of ecosystem to be modeled, and the breadth and quality of input data needed to run the models.

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Table 1. Ecosystem type and climatic region for which each GCTE-SOMNET model has been evaluated (ecosystem separated from climatic region by hyphen)

Model	Ecosystem-climatic region	Reference
ANIMO	G-CT, A-CT	Rijtema and Kroes (1991)
CANDY	A-CT, A-WTST, G-CT, H-CT	Franko et al. (1995), Franko (1996), Franko et al. (1997)
CENTURY	N-CTB, N-CT, N-WTST, N-T, G-CT, G-WTST, G-T, A-CT, A-WTST, A-T, F-CT, F-WTST, F-T	Parton et al. (1988), Kelly et al. (1997)
Chenfang Lin Model	None - growth chamber only	Lin et al. (1987)
DAISY	A-CT, A-WTST, G-CT	Svendsen et al. (1995), Mueller et al. (1996)
DNDC	A-CT, A-WTST, A-T, G-CT	Li et al. (1994), Li et al. (1997)
DSSAT	None specified	Hoogenboom et al. (1994)
D3R	A-CTB, A-CT, A-WTST	Douglas and Rickman (1992)
Ecosys	A-CTB, A-CT, A-WTST	Grant et al. (1993a, 1993b), Grant (1995)
EPIC	A-CT, A-WTST, A-T	Williams (1990)
FERT	A-CT, A-WTST	Kan and Kan (1991)
GENDEC	N-PSP, G-WTST	Moorhead and Reynolds (1991)
Hurley Pasture ITE (Edinburgh) Forestry Model	N-CT, G-CT, F-CT	Thornley and Verberne (1989), Thornley and Cannell (1992), Arah et al. (1997)
ICBM	A-CTB, A-CT	Andrén and Kätterer (1997)
KLIMAT-SOIL-YIELD	A-CTB, A-CT	Sirotenko (1991)
McCaskill and Blair CNSP Pasture Model	N-CT, G-CT, G-WTST, G-T	McCaskill and Blair (1990a, 1990b)
Model of Humus Balance	A-CTB, A-CT	Schevtsova and Mikhailov (1992)

Table 1. continued --

Model	Ecosystem-climatic region	Reference
MOTOR	A-CT, A-T, G-CT, H-CT	Whitmore (1995), Whitmore et al., (1997)
NAM SOM	N-CTB, N-CT, A-CT	Ryzhova (1993)
NC SOIL	N-CTB, N-CT, N-WTST, A-CT, A-WTST, G-CT	Molina et al. (1983), Molina et al. (1997)
O'Leary Model	A-CT	O'Leary (1994)
Q-Soil	A-CTB, F-CTB, F-WTST	Ågren and Bosatta (1987)
RothC	N-CT, G-CTB, G-CT, G-WTST, G-T, A-CTB, A-CT, A-WTST, A-T, F-CT, F-WTST, A-T	Jenkinson and Rayner (1977), Coleman et al. (1997)
SOCRATES	G-WTST, A-CT, A-WTST, A-T	Grace and Ladd (1995)
SOMM	N-PSP, N-CTB, N-CT, N-WTST, N-T, G-CT, G-WTST, G-T, F-PSP, F-CTB, F-T	Chertov and Komarov (1996)
Sundial	A-CT, A-WTST, A-T, G-CT	Smith et al. (1996e), Bradbury et al. (1993)
Verberne	G-CT, A-CTB, A-CT, A-WTST, F-CT	Verberne et al. (1990)
VOYONS	G-CT, F-CT	André et al. (1994)
Wave	G-CT, A-CT, A-WTST	Vanclouster et al. (1995)

Key: Ecosystem: N = natural vegetation, G = grassland (managed and unmanaged), A = arable, H = horticulture, F = forestry/woodland; Climatic region: PSP = polar / sub-polar, CTB = cold temperate boreal, CT = cool temperate, WTST = warm temperate / sub-tropical, T = tropical.

Table 2. Broad categorization of input requirements for each GCITE-SOMNET model

Model	Timestep	Meteorology	Soil and plant	Management	OUTPUTS
					Soil contents

Table 2. Broad categorization of input requirements for each GCTE-SOMNET model

Model	Timestep	INPUTS			Management	OUTPUTS	Notes
		Meteorology	Soil and plant	Soil outputs			
ANIMO	Day, week, month	P, AT, Ir, EvW	Des, Lay, Imp, Cl, OM, N, pH	Rot, Til, Fert, Man, Res, Irr, AtN gas	C, N, W, ST, ST, gas		
CANDY	Day	P, AT, Ir	D, Imp, W, N, C, Wi, PD, Nup	Rot, Til, Fert, Man, Res, Irr, AtN gas	C, N, W, ST, ST, gas		
CENTURY	Month	P, AT	W, Cl, OM, pH, C, N	Rot, Til, Fert, Man, Res, Irr, AtN 14C, N, W, ST, gas	C, BioC, 13C, ST, gas		
Chengang Lin	Day	ST	OM, BD, W	Man, Res	C, BioC, gas		
DAISY	Hour, day	P, AT, Ir, EvG	Lay, Cl, C, N, pH, PS	Rot, Til, Fert, Man, Res, Irr, AtN W, ST, gas	C, BioC, N, W, ST, gas		
DNDC	Hour, day, month	P, AT	Lay, Cl, Om, pH, BD	Rot, Til, Fert, Man, Res, Irr, AtN W, ST, gas	C, BioC, N, W, ST, gas		
DSSAT	Hour, day, month, year	P, AT, Ir	Des, Lay, Imp, W, Cl, PS, OM, ph, C, N	Rot, Til, Fert, Man, Res, Irr	C, BioC, N, W, ST	Decision support shell incorporating a range of models	
D3R	Day	P, AT	Y, PS	Rot, Til, Res	Decomposition of surface and buried residue	Decomposition of surface and buried residue	

Table 2. continued --

Model	INPUTS			Management	OUTPUTS		Notes
	Timestep	Meteorology	Soil and plant		Soil outputs		
Ecosys	Minute, hour	P, AT, Ir, WS, RH	Lay, W, Cl, CEC, Rot, Til, Fert, PS, OM, pH, N, Man, Res, Irr, BD, PG, PS	Man, Res, Irr, AtN	C, BioC, N, W, ST, pH, Ph, EC, gas, ExCat		
EPIC	Day	P, AT	Lay, Imp, W, Cl, OM, pH, C, BD, W ₁	Rot, Til, Fert, Man, Res, Irr	C, BioC, N, W, ST		
FERT	Day	P, AT, WS	Des, Lay, W, Cl, OM, pH, C, N, BD, W, Ph, K, Nup, Y, PS	Rot, Til, Fert, Man, Res, Irr	C, N, Ph, K		
GENDEC	Day, month	ST, W	W, InertC, LQ	Can be used - not essential	C, BioC, N, gas, LQ		Decomposition model
Hurley Pasture ITE (Edinburgh) Forestry Model	Day	P, AT, Ir, WS	W, Cl, PS	Rot, Fert, Irr, AtN	C, BioC, N, W, gas		
ICBM	Day, year	Combination of weather and climate	Many desirable: none essential	C inputs to soil	C		Simple two-component model solved analytically
KLIMAT-SOIL-YIELD	Day, year	P, AT, ST, Ir, EvG, EvS, VPD, SH	Des, Lay, Imp, W, Cl, PS, OM, pH, C, N	Fert, Man, Res, Irr	C, BioC, N, W, ST		

Table 2. continued --

Table 2. continued --

Model	Timestep	Meteorology	INPUTS		OUTPUTS		Notes
			Soil and plant	Management	Soil and plant	Soil outputs	
McCaskill and Blair CNSP Pasture Model	Day	P, AT, Ir	Lay, Inp, W, Cl, CEC, OM, pH, C, N, PS, AS	Fert	C, N, W, ST		
Model of Humus Balance	Year	Climate based on P and AT	Des, Lay, PS, OM, pH, C, N	Rot, Fert, Man	C, N		Statistical model
MOTOR	User specified	P, AT, EvG	Des, OM	Rot, Til, Fert, Man	C, BioC, 13C, 14C, gas		
NAM SOM	Year	P, AT	Des, PS, OM, Ero	Man, RES	C, BioC		
NC SOIL	Day	ST (P, AT)	W, OM, C, N	Fert, Man, Res	C, BioC, 14C, N, 15N, gas		
O'Leary Model	Day	P, AT	Lay, W, Cl, pH, N	Til, Fert, Res	C, BioC, N, W, ST, gas, ResC, ResN		Wheat-fallow rotations only
Q-Soil	Year	Optional	C, N	Rot, Fert, Man, Res, AtN	C, BioC, 13C, N		
RothC	Month	P, AT, EvW	Cl, C, Inert C (can be estimated)	Man, Res, Irr	C, BioC, gas, 14C		
Socrates	Week	P, AT	CEC, Y	Rot, Fert, Res	C, BioC, gas		
SOMM	Day	P, ST	OM, N, AshL, NL	Man	C, N, gas		

III. Modeling SOC Dynamics at the Regional Level – Current Approaches

The modeling of SOC dynamics at the regional level spans a continuum between extremely simple approaches whereby empirical relationships are assumed to apply over large areas, to complex approaches whereby dynamic simulation models are linked to spatially explicit data, usually using Geographical Information Systems (GIS), in order to account for spatial differences in meteorology, soil and land-use. A theoretical discussion of issues involved in upscaling can be found elsewhere (Smith, 1996). Examples of simple approaches are given in such papers as Gupta and Rao (1994), Smith et al. (1996c), Smith et al. (1997b, 1997c) and Smith et al. (1998b). In the above-mentioned papers by Smith et al., the authors use simple statistical relationships to estimate changes in soil C pools over 100 years for the whole of Europe (to as far east as the Baltic States). The approach relies upon establishing relationships between a range of land management practices and changes in SOC over time, derived from 42 European long-term experiments (Smith et al., 1996d), and applying these changes to soil carbon pools calculated from soil organic matter maps of Europe. Yearly estimates of the carbon sequestration potential for six European scenarios based on this simple approach are shown in Figure 1.

Simple approaches such as those described above take no account of local variations in meteorology and soil. To account for such differences, spatially explicit data needs to be used, often through coupling a dynamic simulation model to a GIS database. Examples of this approach are given for the EPIC model in Lee et al. (1993), for CENTURY by Donigan et al. (1994), and for RothC by Parshotam et al. (1995) and Falloon et al. (1998). Details of the latter study are given in section VI below. Such approaches allow spatial variations in meteorology, soil and land-management to be accounted for explicitly, as well as allowing changes in SOC to be visualized spatially. Because of these advantages, the coupled simulation model-GIS system is the preferred option for regional SOC studies and is being used by European research consortia in the EU-funded modular modeling activities ETEMA (European Terrestrial Ecosystem Modeling Activity) and MAGEC (Modeling Agroecosystems under Global Environmental Change).

IV. Potential Pitfalls Associated with Large Scale Modeling of SOC Dynamics in Tropical Ecosystems

Despite model applications at large (global) spatial scales (CENTURY: Parton et al., 1987; Potter et al., 1993; Schimel et al., 1994; and RothC: Post et al., 1982; Jenkinson et al., 1991; Post et al., 1996; King et al., 1997), modeling of carbon dynamics at the regional level and higher presents a number of problems, the most important of which are outlined below.

The most obvious problem associated with large scale modeling in the tropics is the application of models to conditions other than those to which they were parameterized. Most models were originally developed for use in a specific climate (often cool temperate) in a specific ecosystem on a limited range of soil types. These difficulties can be overcome by evaluating the model on data from within the new region (see Table 1) to check that the models are performing well and, if necessary, to recalibrate the models for the specific, local conditions. Examples of the evaluation of one SOM model, RothC, in semi-arid and tropical ecosystems are presented in section V.

The simulation of carbon turnover at depth often presents a problem in that many of the models used for large-scale modeling are parameterized as single layer, topsoil models. RothC for example was originally designed to describe the top 23 cm of soil (Jenkinson and Rayner, 1977; Coleman and Jenkinson, 1996a), while CENTURY was designed to simulate the top 20 cm of soil (Parton et al.,

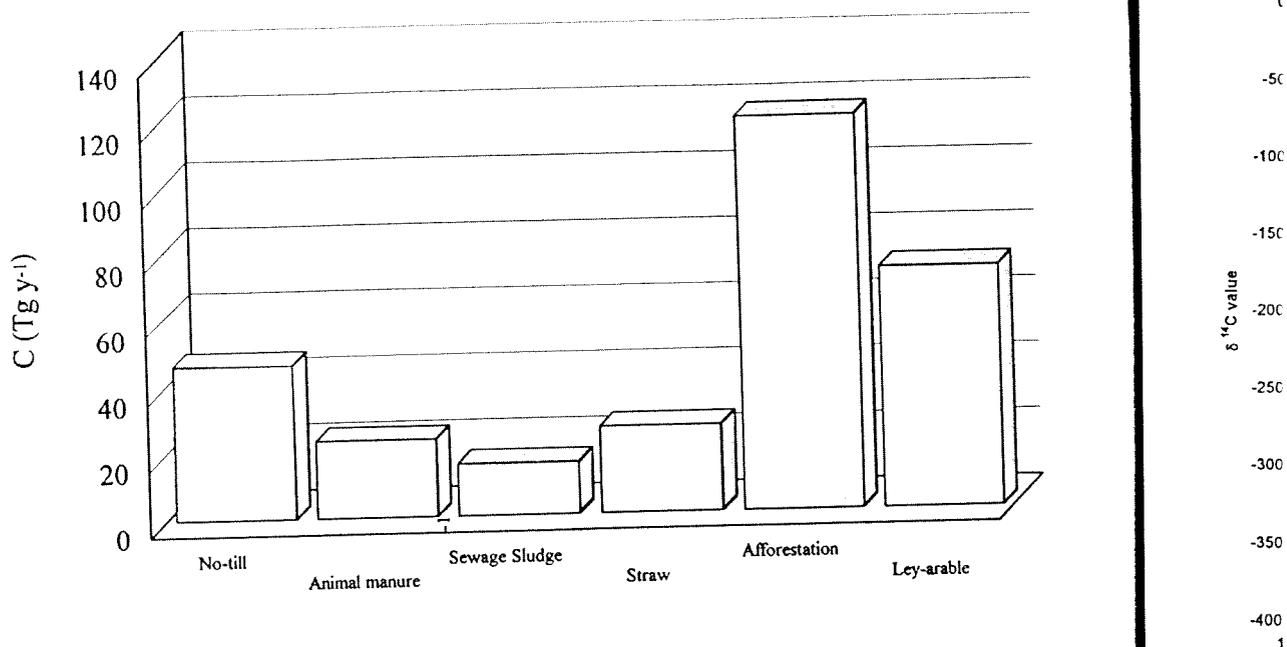


Figure 1. Figures are for the whole of Europe excluding most of the former Soviet Union but including Belarus and the Ukraine (total land area = 490 M ha; arable land area = 135 M ha; SOC content to 30 cm in arable land = 7.18 Pg). All values were estimated using (a) soil carbon contents as described in Smith et al. (1997b, 1997c), and (b) relationships between yearly changes in soil organic carbon content and management practices revealed by relevant European field experiments. No-till assumes conversion of all arable agriculture to no-till. Animal manure figures are for application of animal manure at 10 t ha⁻¹ y⁻¹ to all arable land (Smith et al., 1997b, 1997c). Sewage sludge figures are for application of sludge at 1 t ha⁻¹ y⁻¹ which would be sufficient to cover about 11% of arable land in Europe (Smith et al., 1997b, 1997c). Straw figures are for the incorporation of all cereal straws into the land on which the crops were grown. There is sufficient straw to provide an incorporation rate of about 5 t ha⁻¹ y⁻¹ (Smith et al. 1997b, 1997c). Afforestation is for natural woodland regeneration on 30% arable land which is the upper limit predicted to be surplus to arable requirements by 2010. It includes the carbon mitigation potential of the wood produced assuming 50:50 biofuel:bioproduct utilization of the wood (Smith et al., 1997b, 1997c). Ley-arable (or mixed cropping) figures are for extensification of arable agriculture (leaving current grassland at present level). The predicted 30% surplus of arable land by 2010 could be used to allow less intensive use of all land. The pasture or ley phases could then be used for less intensive animal production by raising pigs and poultry in outdoor units (Smith et al., 1997b, 1997c).

1987). Post et al. (1982), in their application of RothC, assumed that most of the carbon was in the upper layers of soil but applied the model with the same SOM turnover rate constants to a depth of 1 m. Differences in the rate of SOM turnover at depth may have profound implications for the overall SOM dynamics of an ecosystem. Figure 2 shows the predicted differences in average radiocarbon age of SOM at different depths for different rates of SOM turnover. The model (RothC) was fitted to radiocarbon dates (expressed as $\delta^{14}\text{C}$ values) measured on soil samples taken in 1881 at three depths,

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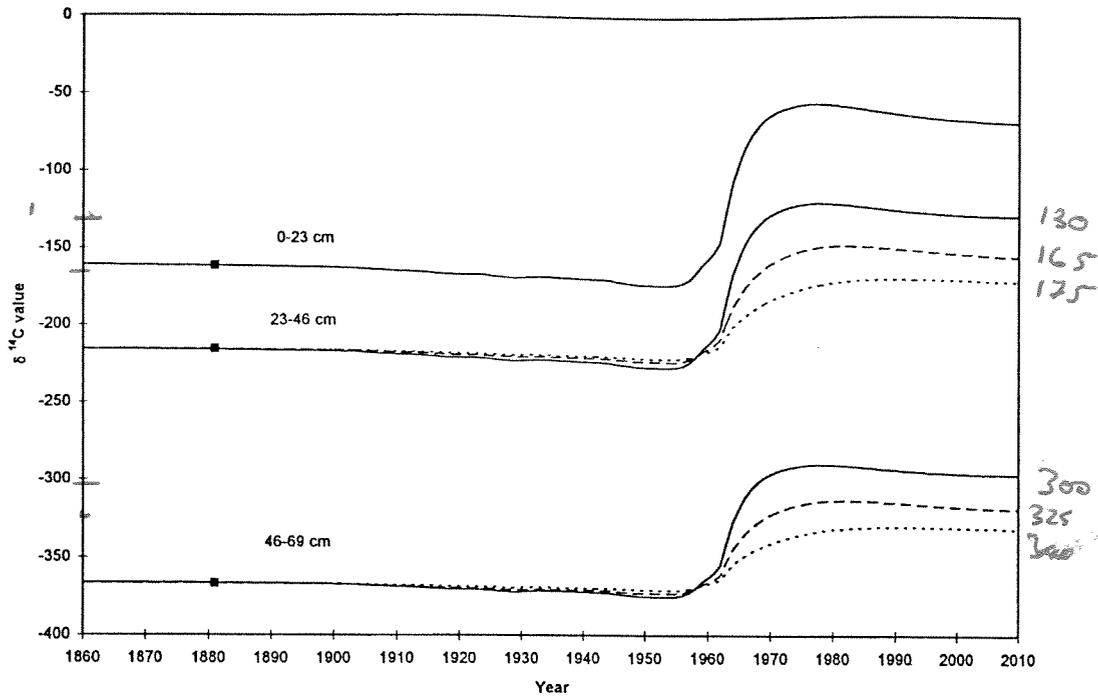


Figure 2. Difference in average radiocarbon content of SOM at different depths in the unfertilized control plot of the Broadbalk Continuous Wheat Experiment at Rothamsted assuming different rates for SOM turnover in deeper soil layers. Depths 0–23, 23–46 and 46–69 cm are labelled. Solid lines show predicted $\delta^{14}\text{C}$ value using standard turnover rate constants, broken lines show values assuming 1/2 standard rate constant, and dotted lines show values assuming 1/4 standard rate constant. See text for further details.

0–23, 23–46 and 46–69 cm, on the Broadbalk Continuous Wheat Experiment at Rothamsted, UK. The model was then run using the standard turnover rate constants for each depth and using rate constants that were 1/2 and 1/4 the standard rates for depths 23–46 and 46–69 cm. A thermonuclear test (“bomb”) effect can be seen at all depths during the 1960s (see Jenkinson et al., 1992).

Radiocarbon measurements clearly show (Trumbore, 1993) that SOC becomes older down the profile. SOC models should not be applied unmodified to subsoils when calculating SOC sequestration potential.

All SOM models are highly dependent upon the quality and quantity of carbon inputs to the soil system. Plant litter quality is frequently expressed as a C/N ratio, lignin/N ratio, or is fitted empirically to give a specified decomposable/resistant plant material ratio (see Molina and Smith, 1997; McGill, 1996). For the quantity of carbon returned to the soil, which is a critical factor in determining the accurate prediction of SOM dynamics by a model, some models (e.g., CENTURY; Parton, 1996) have simple NPP models which provide C inputs for a range of plant types, others (e.g., SUNDIAL; Smith et al., 1996e) have a series of default C inputs (which for agricultural crops is assumed to vary with yield) for various plant species derived from literature values, while others (e.g., RothC; Coleman and Jenkinson, 1996a) require that plant C inputs be entered. For any of these approaches, small errors in

the amount of plant C returning to the soil can lead to large errors in predicted SOM dynamics. For this reason, plant C returns must be estimated effectively in any regional scale model application. In the GCTE approach to regional scale SOC modeling (see Section VII), it is intended that RothC and CENTURY will be given identical NPP estimates (either modeled or estimated from remotely-sensed data) so that this source of discrepancy between the models is removed.

The final potential problem addressed in this section is that of data adequacy. Models are often initially tested against data collected from detailed and well controlled experiments. Data of this quality cannot be collected for each portion of land for which a model will be run at large scales; the data that are available are necessarily more crude. While it is possible to collect good quality data on soil characteristics by soil survey, and good quality data on land-use and recent land-use change from remotely sensed data (aerial photographs and satellite imaging), it is often far more difficult to gain quality information on land-use history. Details of land-use history are essential for establishing initial SOM pool sizes—a site cleared from forest for arable use 10 years ago will have very different characteristics from a site cleared 200 years ago. This presents fewer problems when large areas of a region are still in a natural state, for example in uncleared portions of the Brazilian rainforest, but may cause significant problems in areas where land-use change has occurred over the past 200 or so years, e.g., many agricultural areas in North America. In many cases assumptions need to be made about land-use history. Where experimental sites exist within the region, the data can be used to “ground truth” the assumptions made regarding land-use history.

The potential pitfalls outlined in this section make it essential that models are well tested and that all shortcomings and uncertainties in the input data are considered when interpreting modeled regional results. Notwithstanding, the use of dynamic simulation models linked to GIS databases provides our best predictive tool for assessing the impacts on SOC of current and future environmental change.

V. Modeling SOC Dynamics in Semi-arid and Tropical Ecosystems – Some Examples

In this section examples of the application of one SOM model, RothC, to semi-arid and tropical ecosystems are presented beginning with a recent example of the application of RothC in a semi-arid agroecosystem in Syria and then the application of RothC to a tropical forest-pasture chronosequence in Brazil.

A. Modeling SOC Dynamics in a Semi-arid Region in Syria

Figure 3 shows the measured and predicted changes in SOC for the ICARDA site at Tel Hadya in Syria (Jenkinson et al., 1998) for two contrasting rotations: wheat (*Triticum aestivum*)-medic (*Medicago* spp.) and wheat-fallow. For calibration, the model was fitted to a measurement of SOC in 1993 on each rotation which was sampled independently of the main experiment.

Model performance can be evaluated quantitatively using statistics such as Root Mean Square Error (RMSE; Smith et al., 1996f). A full description of the range of statistics available for quantitative model evaluation is given in Smith et al. (1996f) and Smith et al. (1997e). As seen in Figure 3, the modeled and measured values are close for the wheat-fallow rotation (RMSE = 3.56) but less close for the wheat-medic rotation (RMSE = 6.19). This example demonstrates the general applicability of RothC in semi-arid agroecosystems but also shows that inaccurate site specific calibration can lead to discrepancies between modeled and measured values.

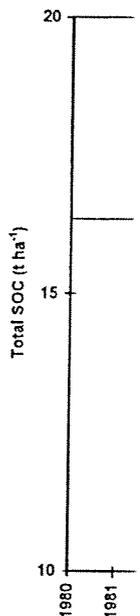


Figure 3. Modelled and measured Total SOC (t ha⁻¹) for wheat-fallow (bro) and wheat-medic (1993 only) at the ICARDA site at Tel Hadya in Syria (Jenkinson et al., 1998).

B. Modeling

Data on C tu of tropical p et al., 1995) CS2). Native giving pastu of these two data to estim C inputs, the

The initi: measurement: (IOM) conte: ($\delta^{14}\text{C} = 109$ (1996b). A n for the mode 18.3–34.5%,

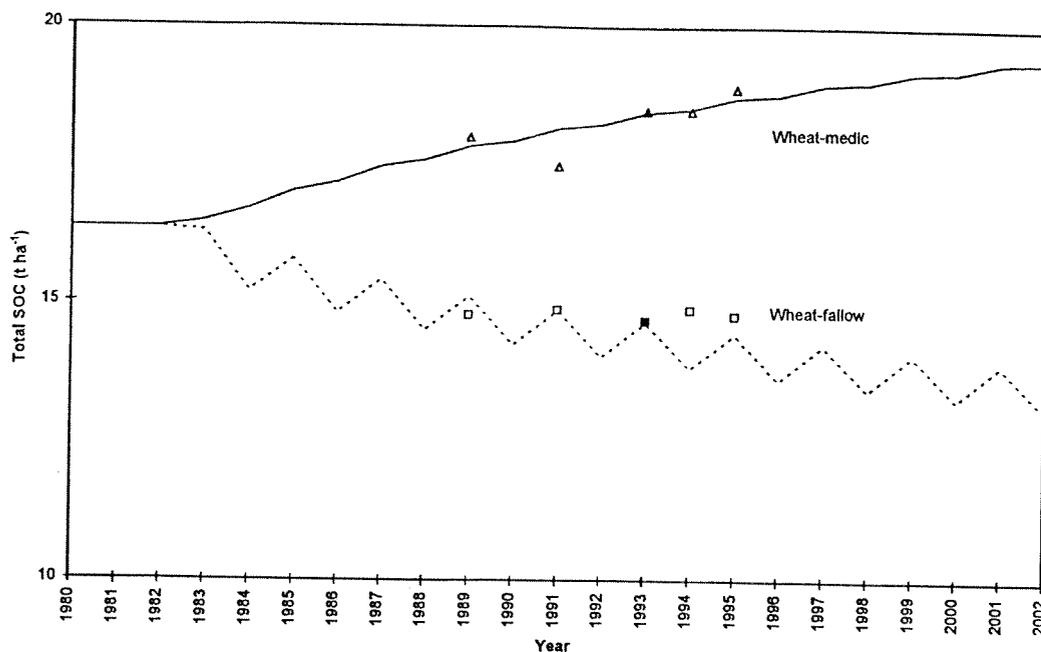


Figure 3. Measured and predicted (using RothC) changes in SOC for two different rotations from the ICARDA two-course rotation experiment at Tel Hadya, Syria: wheat-medicago (solid line) and wheat-fallow (broken line). Measured data are shown as open symbols while independent calibration data (1993 only) are shown as solid symbols.

B. Modeling a Tropical Forest-pasture Chronosequence from Brazil

Data on C turnover were collected in 1992 from Fazenda Nova Vida, Rondônia, Brazil on two series of tropical pasture sites which were converted from natural forest between 1972 and 1992 (Moraes et al., 1995) forming two tropical forest-pasture chronosequences (hereafter referred to as CS1 and CS2). Native forest was cleared for pasture on these plots in 1972, 1979, 1983, 1987, 1989 and 1992 giving pastures aged 20, 13, 9, 5 and 3 years in 1992, as well as an area of native forest. The modeling of these two chronosequences using RothC are presented here. CS1 was used to fit the model to the data to estimate the yearly C inputs required to give observed SOC values (calibration). Using these C inputs, the model was then run independently for CS2.

The initial C content of the soil (0–30 cm) under native forest in 1972 was estimated from measurements in 1992 as 40.8 t C ha⁻¹ for CS1 and 41.2 t C ha⁻¹ for CS2. The inert organic matter (IOM) content was estimated to be 1.9 t ha⁻¹ by fitting the model to the mean radiocarbon age value ($\delta^{14}\text{C} = 109.8$ for 0–30 cm) for the CS1 native forest site as described in Coleman and Jenkinson (1996b). A mean clay content (0–30 cm) across each of the different chronosequence sites was used for the model runs, though the clay contents differed quite widely (CS1: mean = 28.7%; range = 18.3–34.5%, CS2: mean = 22.9%; range = 10.3–39.86%).

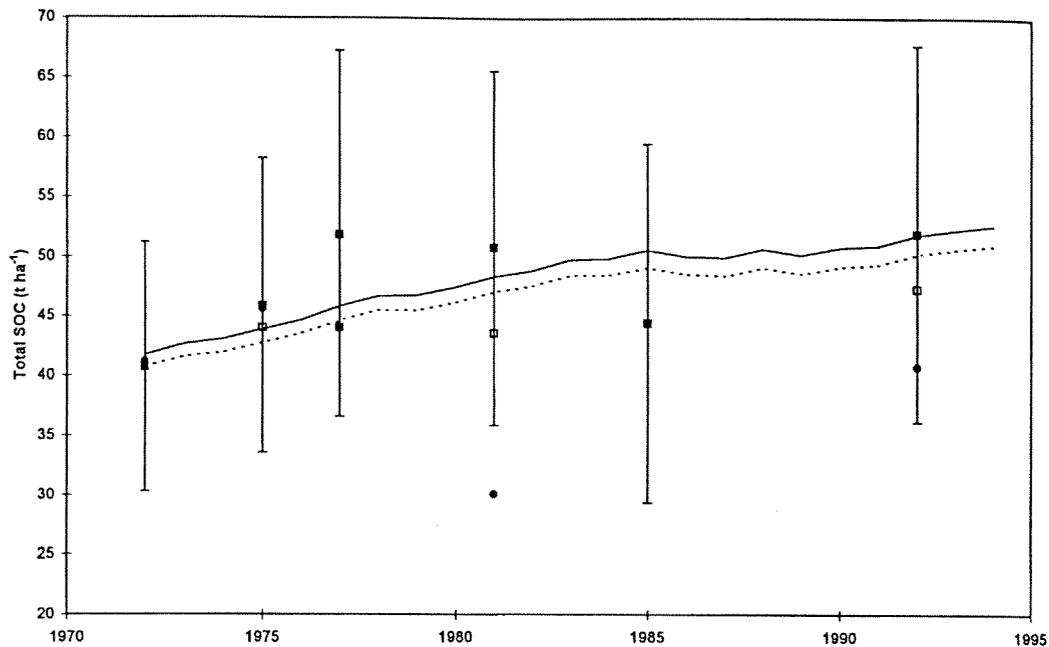


Figure 4. Modeled and measured C turnover (using RothC) on two tropical forest-pasture chronosequences (Moraes et al., 1995) at Fazenda Nova Vida, Rondônia, Brazil. Native forest was cleared for pasture on these plots in 1972, 1979, 1983, 1987, 1989 and 1992, giving pastures aged 20, 13, 9, 5 and 3 years in 1992 and an area of native forest. Chronosequence 1 (CS1) measured SOC points are shown by ■ (with standard error bars); modeled SOC for CS1 is shown by ____; measured SOC points for CS2 are shown by ● (standard error bars omitted for clarity); modeled SOC for CS2 (using mean clay%) is shown by -----; and modeled SOC points for CS2 (using actual clay%) are shown by □. See text for further details.

For CS1, the model was first run to equilibrium using a meteorological data file containing the 20-year local averages of monthly precipitation, air temperature and evaporation. The model needed an annual input of carbon under native forest of $7.6 \text{ t C ha}^{-1} \text{ y}^{-1}$ to account for the equilibrium SOC content of CS1. The model was then run for the pasture phase using local monthly meteorological records. The model predicted an annual input of carbon under pasture of $12.15 \text{ t C ha}^{-1} \text{ y}^{-1}$ to account for the SOC content of CS1. Using these C inputs for forestry and pasture, the model fit is reasonable ($RMSE = 7.93$; Figure 4). Variations in the measured values are attributable to differences in soil clay content at different chronosequence sampling sites (see below).

The model was then run again for CS2 using the same yearly C inputs (but using the CS2 mean clay content; 22.9%). Figure 4 shows the modeled SOC for CS2 ($RMSE = 19.48$) which is predicted to increase in a similar manner to CS1. The reason for the poor fit is the variation in clay content at each chronosequence site giving a scatter in the measured points; the lower than average clay content at sites corresponding to 1981 and 1992 in the chronosequence lead to a lower SOC content. A similar

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trend can be seen for CS1 (Figure 4) where the 1985 measured point is lower due to a clay content of 25.8% compared to the mean (28.7%).

To account for variations in clay content, the model was run again using the same annual C inputs, but with the actual clay contents. This provided a modeled point for comparison with each measured point, but the modeled points are derived from different model runs and therefore cannot be joined on the graph. The predicted points modeled in this manner are also shown in Figure 4 and show a much better fit ($RMSE = 4.75$); better in fact than the calibration run for CS1. This demonstrates that variations in clay content at different sites can have a profound affect on C accumulation and highlights the weakness of chronosequence data (where each sample is taken from a different plot) compared to long-term experimental data (where each sample is taken from the same plot). Had the clay content been the same at each site (as assumed in the first CS2 run), the model predicts a steady increase in SOC between 1972 and 1992.

It is interesting to note that plant C returns required to explain the observed increase in SOC after conversion of forest to pasture, are greater under pasture than under native forest. As well as greater inputs, there is a change in litter quality (i.e., the litter becomes more decomposable) under pasture, so that higher C inputs are required to maintain the same SOC level. Moraes et al. (1995) reported similar findings using the same data. Using $\delta^{13}C$ values, they found that carbon derived from forest (Cdf) decreased sharply during the first 9 years until a stable value (about half the total SOC) was reached after 20 years, while carbon derived from pasture (Cdp) increased more rapidly than Cdf decreased. The total SOC (0–30 cm) after 20 years was about 17 to 20% higher under pasture than under native forest. The work of Veldkamp (1994) suggests that the major source of SOC under pasture is from below-ground net primary production. A similar increase in SOC has been observed elsewhere in the Amazon after deforestation (in areas that have not been subjected to severe burning or overgrazing; Moraes et al., 1995; Neill et al., 1997), though depletion of soil C has also been reported (e.g., Allen, 1985; Mann, 1986; Detwiller and Hall, 1988). Despite these increases in SOC, only about 10% of the total ecosystem C lost after deforestation (due to tree removal, burning, etc.) can be recovered (Fearnside, 1997; Neill et al., 1997).

VI. Linking Dynamic Simulation Models to Spatially Explicit Datasets – An Example

In section III the advantages of linking dynamic simulation models to GIS databases for regional simulation and prediction of SOC dynamics were outlined. In this section, it is shown how a C turnover model (RothC) and a GIS database (using the ArcView platform) can be linked. For demonstration purposes, the impacts on SOC after 100 years of the afforestation of all current arable land in a nontropical study area are presented. This scenario was chosen because it shows clear changes in SOC, not because it is regarded as a realistic land-use change option. Full details of this study are given in Falloon et al. (1998).

The study area was a central region in Hungary (an area of 24,804 km²) bounded by coordinates (UTM 34) 5183816.64, 325048.59, 5340133.61, 472979.10. Soil data were taken from the HunSOTER database of Hungary (scale 1:500,000; Pasztor et al., 1996; Szabo et al., 1996) containing 275 representative soil profiles within the area. Variables for the uppermost horizon for SOC (%), clay % and soil bulk density were used. The profile data were linked to the 351 SOTER unit polygons (representing areas with unique soil, land form and lithology characteristics). The dataset was used to calculate the soil IOM content in the absence of radiocarbon data (see Falloon et al., 1997) and SOC (t C ha⁻¹) to 30 cm depth.

Land-use data were taken from the CORINE database for Hungary (scale 1:100,000; Büttner, 1997; Büttner et al., 1995a, 1995b) with 6470 polygons within the study area. The 44 original land-use codes were rationalized into 4 codes: arable, grassland, forestry and "not used" (includes marsh, water bodies and urban areas). Land use polygons were linked to meteorological data from the nearest of 17 meteorological stations, each providing long-term averages of mean monthly temperature, rainfall, and evaporation from 1931 to 1960 (Varga-Haszonits, 1977). This provided a linked land-use/meteorological layer.

The soil layer was overlaid upon the linked land-use/meteorological layer giving 12086 polygons representing a unique combination of land-use, soil, and meteorology. Excluding those land-uses not used, 9888 polygons were used in the modeling exercise.

The original source code of RothC was altered to take input from a fixed width ASCII file output from the GIS and write results to a new ASCII file, which could then be loaded into Excel, Access and GENSTAT for analysis and ArcView for visualisation. The model was run to equilibrium using default plant input values derived from a dataset of equilibrium land-use treatments at 60 SOMNET sites across the globe (default plant inputs were $3.55 \text{ t C ha}^{-1} \text{ y}^{-1}$ for arable, $3.72 \text{ t C ha}^{-1} \text{ y}^{-1}$ for grasslands, and $7.09 \text{ t C ha}^{-1} \text{ y}^{-1}$ for forestry). The modeled and measured SOC values were then matched by the model by analytically solving for the plant C inputs required to achieve the observed equilibrium SOC value. For each arable-land polygon, the model then ran for a further 100 years, using a hypothetical scenario of immediate afforestation (i.e., with default forestry plant C inputs and with the default forestry plant litter quality factor). The model run for all 9888 polygons was completed on a 66 MHz 486 personal computer in just 1.5 hours.

The total SOC stock for the whole area was calculated as 1.40 Tg, which increased to 1.89 Tg after 100 years. The change in SOC (t C ha^{-1}) 100 years after all arable land was afforested can be seen in Figure 5.

This is a change in SOC (0–30 cm) of 35% after 100 years over the whole area (i.e., $0.35\% \text{ y}^{-1}$ on average with more rapid changes earlier). For the same scenario, using the regression equation for the yearly percentage change in SOC of Smith et al., (1997b), the total SOC stock 100 years after afforestation of all arable land would be 1.97 Tg, slightly higher than this estimate of 1.89 Tg. However, we have more confidence in the present estimate since we have explicitly accounted for differences in soil type and climate. A more sophisticated approach to estimating NPP or plant C inputs (see section IV) could further improve the accuracy of the estimates presented here.

This simple example, in which a dynamic simulation model is linked to a GIS database, demonstrates a flexible and powerful methodology for assessing the impacts of different scenarios of land-use, management and climate change on SOC at the regional scale.

VII. Modeling the Impact of Land-use Change on Regional Soil Organic Carbon Stock in the Tropics

The spatial analysis method discussed in Section VI is equally applicable to tropical systems (subject to the potential problems outlined in Section IV) and is being developed as a major part of the GCTE soil organic matter research agenda (Ingram and Gregory, 1996). Building on the concept originally outlined by Elliott and Cole (1989) and refined by Paustian et al. (1997a), the strategy involves the integration of a series of approaches: process studies, simulation models and spatial extrapolation to build regional-scale projections of change (Figure 6).

The rationale for this approach is that, while methods based on summation of mapping unit values (e.g., Batjes, 1996) or interpolation (e.g., Moraes et al., 1995) may be suitable for estimating current soil carbon stocks at regional scale, only modeling approaches can give indications of future levels

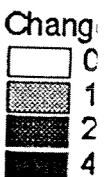


Figure 5. The change in SOC (t C ha^{-1}) 100 years after all arable land was afforested in an area in Central Europe in our scenario.

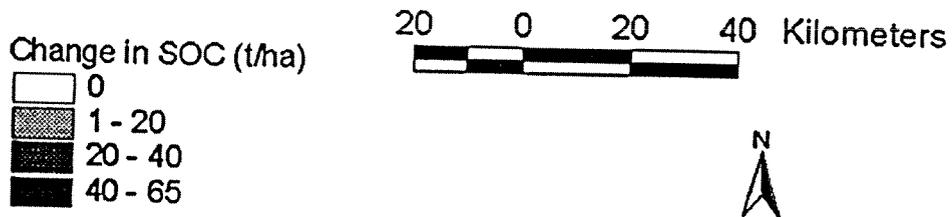


Figure 5. The change in SOC ($t C ha^{-1}$) 100 years after all arable land was hypothetically afforested in an area in Central Hungary. Areas showing no change are non-arable areas and were not changed in our scenario.

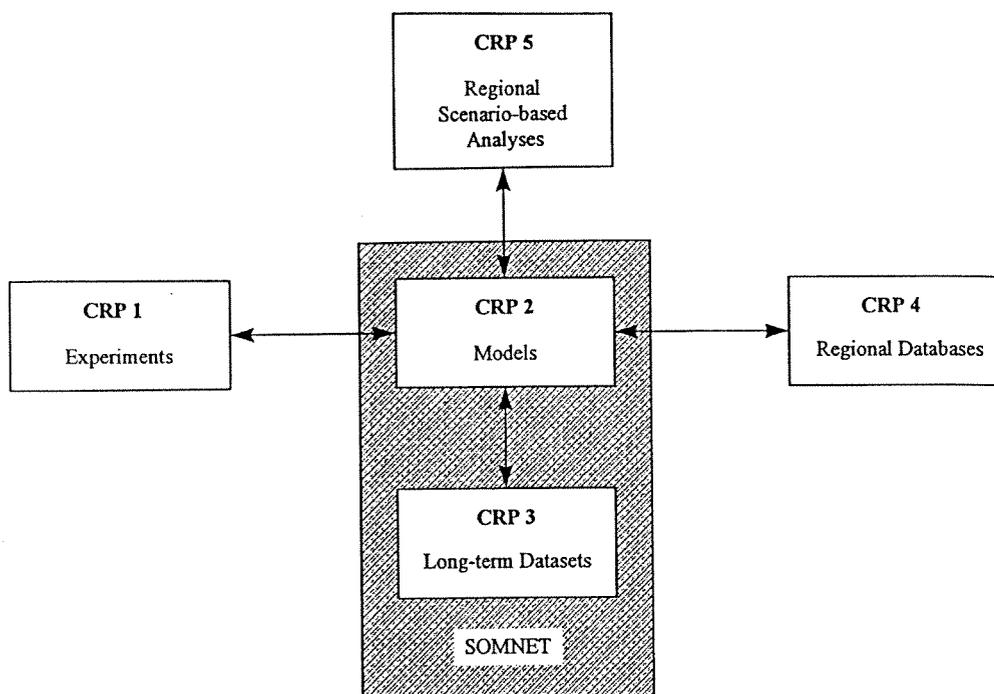


Figure 6. Conceptual framework of the GCTE soil organic matter research focus.

due to changed land-use, land-cover and/or climate. The modeling approach must however be evaluated against the other methods for the current situation. While it may not prove as satisfactory as mapping methods for estimating absolute SOC stocks, it is the only way of conducting scenario-based analyses, especially where the change in SOC stock is of primary interest (i.e., to improve the Climate Convention GHG inventory methodology). Nevertheless, a significant effort will be needed in gathering sufficient data to build adequate data layers to answer given scenario questions. The approach will therefore initially compare modeled estimates of current soil organic carbon stock at regional scale with estimates made by mapping unit methods. The next step is to estimate change over time in SOC stock (i.e., net CO₂ fluxes from soils) at national and sub-national scales as a consequence of change in driving variables, (i.e., climate, land cover, land management). A final step will be to estimate change in the soil organic carbon stock and CO₂ fluxes as a consequence of different policy options to assist in formulating policy options through improved land-use management.

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