
Volume 122, Issue 1
September 2007
ISSN 0167-8809
ELSEVIER
Agriculture Ecosystems & Environment
Special issue
Soil Carbon Stocks at Regional Scales
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Available online at www.sciencedirect.com
ScienceDirect
Agriculture, Ecosystems and Environment 122 (2007) 3–12
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

National and sub-national assessments of soil organic carbon stocks and changes: The GEFSOC modelling system

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Available online 12 February 2007

Abstract

Soil organic carbon (SOC) plays a vital role in ecosystem function, determining soil fertility, water holding capacity and susceptibility to land degradation. In addition, SOC is related to atmospheric CO_2 levels with soils having the potential for C release or sequestration, depending on land use, land management and climate. The United Nations Convention on Climate Change and its Kyoto Protocol, and other United Nations Conventions to Combat Desertification and on Biodiversity all recognize the importance of SOC and point to the need for quantification of SOC stocks and changes. An understanding of SOC stocks and changes at the national and regional scale is necessary to further our understanding of the global C cycle, to assess the responses of terrestrial ecosystems to climate change and to aid policy makers in making land use/management decisions. Several studies have considered SOC stocks at the plot scale, but these are site specific and of limited value in making inferences about larger areas. Some studies have used empirical methods to estimate SOC stocks and changes at the regional scale, but such studies are limited in their ability to project future changes, and most have been carried out using temperate data sets. The computational method outlined by the Intergovernmental Panel on Climate Change (IPCC) has been used to estimate SOC stock changes at the regional scale in several studies, including a recent study considering five contrasting eco regions. This 'one step' approach fails to account for the dynamic manner in which SOC changes are likely to occur following changes in land use and land management.

A dynamic modelling approach allows estimates to be made in a manner that accounts for the underlying processes leading to SOC change. Ecosystem models, designed for site scale applications can be linked to spatial databases, giving spatially explicit results that allow geographic areas of change in SOC stocks to be identified. Some studies have used variations on this approach to estimate SOC stock changes at the sub-national and national scale for areas of the USA and Europe and at the watershed scale for areas of Mexico and Cuba. However, a need remained for a national and regional scale, spatially explicit system that is generically applicable and can be applied to as wide a range of soil types, climates and land uses as possible. The Global Environment Facility Soil Organic Carbon (GEFSOC) Modelling System was developed in response to this need. The GEFSOC system allows estimates of SOC stocks and changes to be made for diverse conditions,

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0167-8809/$ – see front matter
doi:10.1016/j.agee.2007.01.002

providing essential information for countries wishing to take part in an emerging C market, and bringing us closer to an understanding of the future role of soils in the global C cycle.

Keywords: Soil organic carbon; Models; Spatial data; Regional scale; GEFSOC modelling system

1. Introduction

Excluding carbonate rocks, soils represent the largest terrestrial stock of C, holding approximately 1500×10^{15} g C (Batjes, 1996). This is approximately twice the amount held in the atmosphere and three times the amount held in terrestrial vegetation (Smith, 2004a). In most soils (with the exception of calcareous soils) the majority of this C is held in the form of SOC (Batjes and Sombroek, 1997). SOC is vital for ecosystem function, having a major influence on soil structure, water holding capacity, cation exchange capacity and the soils' ability to form complexes with metal ions and store nutrients (van Keulen, 2001). Appropriate management of soils to increase SOC levels can, therefore, increase the productivity and sustainability of agricultural systems (Cole et al., 1997) and, conversely, inappropriate management of SOC can lead to land degradation. An example is the SOC depleting agricultural practices carried out in the Great Plains area of North America during the 1930s, which led to severe land degradation (Paustian et al., 1996).

More recently, soils and SOC have received attention in terms of the potential role they can play in mitigating the effects of elevated atmospheric CO_2. Batjes (1999) estimated that, with changes in land use and appropriate management of agricultural lands, grasslands and forests, soils have the potential to sequester 14 ± 7 Pg C, globally, over the next 25 years. This gives an annual sequestration rate of 0.58–0.80 Pg C, which is equivalent to 9–12% of the anthropogenic CO_2–C produced each year. Bruce et al. (1999) make a slightly more conservative estimate of 0.45–0.61 Pg C yr^{-1} whereas Lal (2004) suggests a potential rate of 0.9 ± 0.3 Pg C yr^{-1}. All estimates show the considerable potential soils could play in this area, even before consideration is given to other environmental benefits that would follow.

The United Nations Framework Convention on Climate Change (UNFCCC) aims to stabilize greenhouse gas concentrations in the atmosphere at a level that limits adverse impacts on the earth's climate. Potential mechanisms cover emission reductions and activities that increase C sinks, including terrestrial sinks. The Kyoto Protocol of the UNFCCC, which provides a mechanism whereby the aims of the UNFCCC can be achieved, requires that the impact of afforestation, reforestation and deforestation on C sinks be reported under Article 3.3 and allows C sinks to be elected under the categories grazing land management, cropland management, forest management and revegetation under Article 3.4 (Smith, 2004b). This applies to the first commitment period, 2008–2012. In order to correctly account for soil C sinks, a commonly agreed system of assessing soil C stocks and changes is needed. This system needs to be generically applicable, being as relevant to soil and climatic conditions in tropical and arid areas as it is to conditions in temperate areas. In this paper we discuss approaches that have been used to assess SOC stocks and changes to date, before outlining a new, generically applicable, coupled GIS/modelling system (The Global Environment Facility Soil Organic Carbon (GEFSOC) System).

2. An issue of scale

Many studies have considered SOC stocks and stock changes at the plot scale, in a range of different ecosystems under varying conditions (Paustian et al., 1992, 1997; Smith et al., 1997; Schelsinger and Lichter, 2001; Leite et al., 2004). Such studies use site specific data sets to make inferences about SOC stocks and changes in relatively homogeneous conditions. Results are also site specific, limiting their wider applicability.

At the other end of the spectrum different authors have attempted to estimate SOC stocks at the global level with varying results (Table 1). These estimates have been based on global soil maps and information on soil C content and other attributes taken from representative soil profiles or pedons. Variability has arisen because of the different mapping approaches and the different number of profiles used. Sombroek et al. (1993), used the revised FAO UNESCO Soils Map of the World in conjunction with soils information from a limited number of soil profiles (400) to derive their estimate of 1200 Pg C. Eswaren et al. (1993), used the 'Major Soils Regions of the World Map' and soils information from 16,000 pedons. However, only 1000 of these were from countries outside the United States and very few were from the tropics. Batjes (1996) proposed revised estimates for global C stocks, using 4353 profiles;

Table 1
Estimates of global soil organic carbon stocks

Study	Global soil C estimate (Pg to a depth of 1 m)
Post et al. (1982)	1400
Buringh (1984)	1427
Kimble et al. (1990)	1061
Sombroek et al. (1993)	1220
Eswaren et al. (1993)	1576
Batjes (1996)	1462–1548

these included some 1800 profiles from Africa, 1000 from Asia and 600 from South America.

Global estimates of SOC stocks have been down scaled to give national and sub-national scale estimates, but such estimates will be based on generalisations and can be misleading. The need for accurate estimates of SOC stocks and likely stock changes at the national and sub-national scale is increasing with national obligations under the various United Nations conventions. For example the UNFCCC requires parties to report terrestrial stocks of C, including C in soils. Such estimates are important for countries wishing to take part in an emerging C market and are particularly relevant to developing or 'non-Annex 1' countries looking to benefit from C enhancing land use changes under CDM (Clean Development Mechanism) projects. National and sub-national scale estimates of SOC stocks and changes are also relevant to the United Nations Convention to Combat Desertification (UNCCD) and the United Nations Convention on Biodiversity (UNCBD), as SOC depleted areas are often synonymous with land degradation and poor biodiversity.

An understanding of SOC stocks and changes at the national and regional scale is necessary to further our understanding of the global C cycle, to assess the responses of terrestrial ecosystems to climate change, and to aid policy makers in making land use/management decisions.

3. Empirical methods for estimating SOC stocks and changes at the national and sub-national scale

There are several examples of national and regional estimates of current SOC stocks (Arrouays et al., 2001; Jones et al., 2005) and of historical changes in SOC content (Bellamy et al., 2005). Such examples take account of the effects of soil type, land use and climate interactions on SOC content. Predictions of future changes in SOC stocks should ideally account for future changes in these interactions.

The Intergovernmental Panel on Climate Change (IPCC) developed a computational method for estimating SOC stock changes that can be used at the national and sub-national scale. An updated version of the method is described in the IPCC Good Practice Guidance (GPG) for Land Use, Land Use Change and Forestry (IPCC, 2004). The method computes projected net stock changes of C over a given period of time (the default period is 20 years), in a one step process. The method can use default information on climate, soil type and land use/management (tillage and productivity) held by the IPCC (a Tier 1 approach) or, if available, country specific data (a Tier 2 approach). One main drawback is that it considers the change in one step (e.g. one stock for year 1 and another for year 20), assuming a linear rate of change over the period. Another drawback is that much of the data available for deriving the empirical factors in the IPCC default approach are from studies in North America and Europe (typically more are available for temperate versus tropical areas and mesic versus arid areas), which may result in bias (IPCC, 2004). Also, because the default method was designed to be as simple as possible and to use limited and highly aggregated data, the method is less well suited for sub-national assessments. Hence, while useful as a default, the IPCC method has some significant limitations. Where data and methods are available, the Good Practice Guidance recommends their use in place of default (Tier 1) methods (IPCC, 2004).

A recent study used the IPCC method to estimate SOC stock changes at the regional scale in five contrasting eco regions: South Eastern Australia, Northern Kazakhstan, The Indian Indo Gangetic Plains, Sweden and Uruguay (Grace et al., 2004). The areas chosen in the study varied in terms of soils, climate and land use as well as potential management strategies for promoting soil C sequestration and economic conditions. The study adapted the IPCC method by using statistically estimated reference C stocks based on detailed in country data. This produced a robust starting point, from which stock change estimates could be made. It also allowed an analysis of the uncertainties associated with stock change estimates. The study used the stock change between years 1 and 20 to calculate an average annual C stock change rate. However such an approach does not account for possible annual fluctuations and the processes underlying SOC stock change. The main aim of the study was to assess C sequestration potential in soils and the economic cost associated with that sequestration. The method used was, therefore, developed to meet this aim. However, typically 'one step' approaches have been designed to answer questions related to static or fixed conditions or specific land use/economic relationships. Extending their use to answer questions on the dynamic response of SOC to land use change might, therefore create difficulties.

Falloon et al. (2002) summarised a number of other approaches that have been used to estimate changes in SOC stocks at the regional scale. Rather than a one step approach, regression approaches have been used, where long term experimental data sets are extrapolated into the future (Smith et al., 2000; Gupta and Rao, 1994). Such studies assume current trends in SOC change will continue, determining future SOC stocks in a given region for which the relationship, developed from a number of long term experiments in the particular region, is taken to be representative. This approach has the disadvantage of assuming that site scale studies can all be treated as representative and equally valid in a single analysis, and that the resulting statistical relationships are representative of a large heterogeneous areas. A more complex regression approach, that takes account of local variability in soil and climatic conditions, uses regressions based on spatially explicit soil databases. This approach was taken by Kern and Johnson (1993) to estimate the impacts of change from conventional tillage to conservation tillage on SOC stocks in the contiguous USA. A similar approach was used by Kotto-Same et al. (1997) to consider the impact of slash and burn agriculture on soil C stocks in the humid forest zone of Cameroon. Falloon et al. (2002) point out that both these regression approaches assume a constant rate of change in SOC over a given period, which is unrealistic, given that many studies have shown rapid initial changes in SOC immediately following land use change, followed by a slower rate of change (Coleman et al., 1997). In accord with other groups (Paustian et al., 1997; Smith et al., 1997) they also point out that an approach is needed that accounts for dynamic changes in SOC. Using dynamic, process based, soil organic matter models, linked to spatial data through geographical information systems (GIS) offers a way of meeting this need (e.g. Smith et al., 2005).

4. Advantages of a modelling approach

There are several advantages to using process based SOM models linked to spatially explicit databases to estimate SOC stocks and changes at the national and sub-national scale, the most obvious being that the approach takes account of the underlying dynamic processes determining SOC stocks. SOC can be divided into several conceptual pools for modelling purposes, with turnover times ranging from days to centuries (Jenkinson, 1990). Stock changes over relatively short timescales can, therefore, be influenced by events (such as land use change), that occurred throughout a site's history. SOM models allow land use and land management histories to be taken into account when projecting SOC stocks of the future. Another advantage of the approach is that it allows identification of geographic areas of C release, or potential for C sequestration, using a range of scenarios for land use/ management and climate change, which is useful for land use planners and policy makers (Falloon et al., 1998).

5. Examples of linked modelling GIS approaches

Paustian et al. (1997) reviewed the use of models to assess soil C at the regional scale. They point to two types of models being used; the first designed for application at the global scale, which they refer to as 'macro scale models' and the second designed for application at the site scale, called 'ecosystem level models'. Macro scale models are designed to work on a coarse scale (thousands of square kilometres) and employ relatively simplistic formula to describe the processes determining SOC turnover. King et al. (1997) used a macro scale model (that operates on a $0.5^\circ \times 0.5^\circ$ grid of the Earth's surface) linked to soils, climate and ecosystem type data, to estimate changes in soil and vegetation C under different climate and atmospheric CO_2 scenarios. Each cell was allocated one of 31 ecosystem types and a soil type derived from the FAO Soil Map of the World. Climate data was obtained from a global network of meteorological stations. Individual model runs were carried out for each 'terrestrial cell' and changes in soil and vegetation C derived. King et al. (1997) acknowledge the drawbacks to this approach, pointing to the large uncertainties associated with using a limited number of ecosystem types, the assumption that an ecosystem type would be uniform over a grid cell and the need to designate grid cells as either 'all terrestrial' or 'all non-terrestrial'. All of these drawbacks, and others, gain in significance when global scale models, such as this are used at the regional, national or sub-national scale. King et al. (1997) acknowledged an increasing preference for using more mechanistic, ecosystem models to make regional scale assessments.

Such ecosystem models are at the other end of the spectrum, designed for use at the plot or farm scale (Paustian et al., 1997). They use complex functions to describe the movement of SOC through a number of different pools, with different residence times. Some also include complex sub-models describing plant productivity, water movement and the turnover of N, P and K. Paustian et al. (1997) describe many of the problems associated with aggregating process functions, designed to describe site scale situations, to make regional scale estimates. This approach does, however, have more potential for describing the actual situation in a given region than a macro scale approach, not least because current knowledge of SOC dynamics is largely based on site scale observations.

Falloon et al. (1998) devised a method of linking the RothC SOC model to spatially explicit soils, land use and climate data via a GIS and used it to estimate regional changes in SOC for a 24,804 km^2 area of central Hungary. RothC splits SOC into four active compartments and a small amount of inert organic matter (Coleman and Jenkinson, 1996). Inputs to the soil must be known, as the model does not estimate plant productivity. Falloon et al. (1998) overlaid regional scale soils, land use and climate information to produce polygons with unique combinations of these attributes. This resulted in $\sim$12,000 polygons. Code was then written which allowed the RothC model to take input data on soils, climate and land use from these polygons and write output data on SOC back to the same polygons. Later work extended the approach to compare estimates from the Century model (Parton et al., 1988) with RothC (Falloon et al., 2002). The link has been further developed to account for changes in NPP, land use and technology and applied to the whole of Europe at $10' \times 10'$ resolution (Smith et al., 2005, 2006).

Ardö and Olson (2003) used a slightly different approach to Falloon et al. (1998) to link spatially explicit data to the Century model in one of the few examples of a regional scale assessment of SOC stock change being made in a non-temperate area. Century is a general ecosystem model with soil C, plant productivity, water movement and nitrogen leaching sub-models (Parton et al., 1988). Ardö and Olson (2003) compiled a spatially explicit database of soil texture, climate and land cover information for a $\sim$262,000 km^2 area in Sudan. Instead of a polygon approach, data was used in a grid form. Each grid cell comprising a unique combination of soil, land use and climate variables, warranted one Century model run. In many cases, grid cells with unique combinations occurred more than once in the given geographic area. This reduced the number of model runs from thousands to hundreds, but still resulted in separate model runs for each unique grid cell.

Wide use of an approach linking spatially defined data to the Century model has been made by a research group working at NREL, Colorado State University, USA. Applications have included state and regional assessments of soil C changes associated with changing land use and management (Paustian et al., 2001, 2002), assessments of C sequestration policies at regional scales (Antle et al., 2002, 2003) and estimation of CO_2 emissions and removals for US soils (EPA, 2006; Paustian et al., in preparation; Ogle et al., in preparation). Paustian et al. (1995) outline the approach they used to link the Century model to spatially defined data sets, including the variables needed to run the model. Climate, soils and land use data sets associated with specific geographic areas are overlain in a GIS to create a set of unique polygons that define the driving variable sets needed for executing Century. Representing variable land management sequences is the most complex component of the system. In the system outlined by Paustian et al. (1995), the number of model runs can be reduced if polygons with the same soil type and climate share the same land use history, even if this is only up to a certain point in time. For example, three polygons may be under a wheat (*Triticum aestivum* L.)/legume (*Glycine max*) system for 5 years, two of these then continue as wheat/legume for the next 5 years whilst one goes into pasture. For the first 5 years all polygons can be described by one model run. The next 5 years will then be described by two model runs, one for the two wheat/legume polygons and one for the pasture polygon. This ability to link periods of land use and land management together in a chain, without having to duplicate model runs for given periods, reduces model running time considerably. This is a considerable benefit when detailed estimations are being made for large areas, for example at the national and sub-national scale.

Paustian et al. (1995) stress the importance of evaluating the model performance in conditions particular to the region under investigation and in this example, use long term experimental data sets (~10–35 years) from across the USA. The authors set out a framework for using site scale experimental data, regional GIS databases and simulation models to make regional scale assessments of SOC stocks and changes (Fig. 1).

The examples outlined above were developed and used in individual countries and regions. The methods and approaches used varied and it is therefore difficult to make cross comparisons between the results produced. None of the studies were carried out using data from tropical regions, yet it is in tropical areas that the largest changes in SOC induced by land use change are likely to occur (Batjes and Sombroek, 1997). A recent project funded by The Food and Agriculture Organisation (FAO) did consider SOC turnover in tropical ecosystems using SOM models and GIS databases. The study was confined to the watershed and district scale and considered three areas, two in Mexico and one in Cuba. In a preliminary report, the authors (Ponce-Hernandez, 2004) made estimations of above ground biomass in the three watersheds using remote sensing data and ground level transect data. They used these data to estimate C in above ground biomass and below ground biomass using multiplication factors. They then used the above ground estimations of C as inputs for two soil C models, RothC and Century. They devised a graphical user interface (GUI) for Century, that allows the user to input the minimum of parameters required to run the model and map results to given geographic areas using a GIS. The 'framework methodology' developed in this study, was designed for the watershed scale and

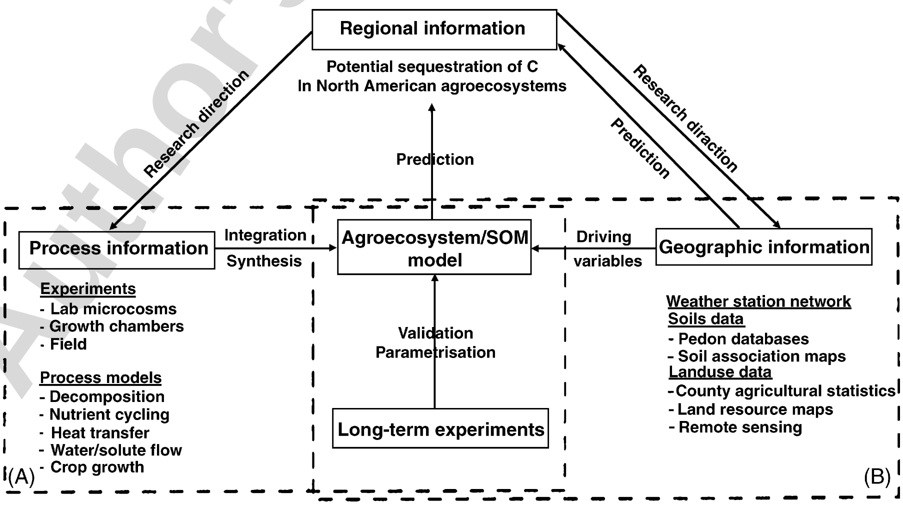

Fig. 1. A conceptual diagram showing the integration of process information, long-term experiment data and site networks, simulation modelling and regional GIS databases. Box A denotes components which can be applied for local scale analyses (i.e. at a particular location) and Box B denotes components which are necessary for regional scale analyses (reproduced from Paustian et al., 1995).

involved much collation of new data, something that is rarely possible at the national and sub-national scale. In addition, restricting the possible input parameters that the user can enter makes the system less specific to the area it is applied to. This is an important consideration when it is being applied to tropical conditions.

6. The global environment facility soil organic carbon (GEFSOC) system

From the discussion so far it can be seen that:

- There are advantages to using a linked SOM/GIS approach to estimating SOC stocks and changes at the national and sub-national scale.
- In order to make comparable national and sub-national estimates of SOC stock changes, a generically applicable system is needed that can be applied to a wide range of soil types climates and land uses.
- Such a system needs to be able to utilise existing readily available data across a range of scales.
- Such a system should maximise use of the complex descriptions of ecosystem function offered by SOM models.
- The system should, however, be easy to use and should run on ‘off the shelf’ computers, available in developing countries, as well as developed countries.

The GEFSOC Modelling System was developed to address the above issues. Models and methods developed by research groups working in the UK and the USA (Paustian et al., 1995, 1997; Falloon et al., 1998, 2002) were built on to develop a generically applicable system for estimating SOC stocks and changes at the national and sub-national scale. The system was developed using data from four contrasting eco regions: the Brazilian Amazon, Jordan, Kenya and the Indian part of the Indo Gangetic Plains. These regions were chosen for their contrasting climates and soil types (Table 2) and because they provide examples, of those areas under-represented by current soil C models. The system uses a graphical user interface (GUI) to allow the user to simultaneously make spatially explicit SOC stock and stock change estimates using two soil C models (RothC and

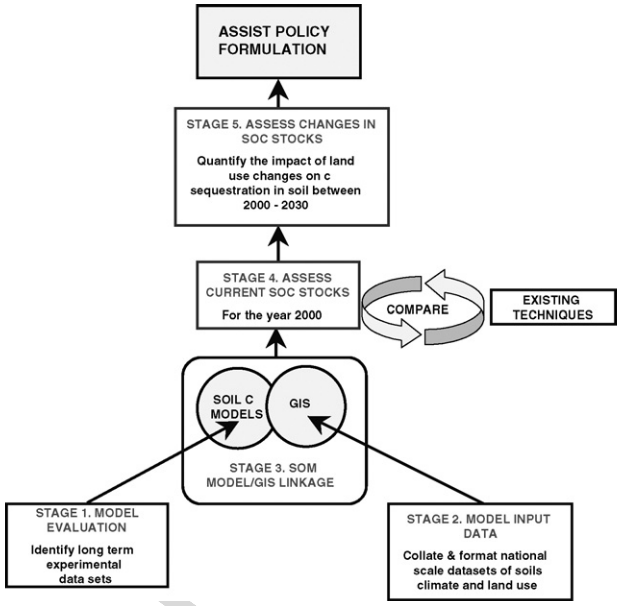

Fig. 2. The five stages of GEFSOC system development.

Century) and the empirical IPCC method. Layers of soils, climate, historical and current land use, and land management data, collated in a consistent format, are linked to the two models used (Century and RothC) and the IPCC method, via GIS. The system itself comprises the GUI and a number of components that run the three methods. Technical details of the system development are given in Easter et al. (2007).

The method used to develop the system involved five stages based on the principles outlined by Paustian et al. (1997) (Fig. 1). The way in which these five stages interact is shown in Fig. 2.

- *Stage 1*: *Model evaluation*. RothC and Century were chosen for the study as they were found to be able to simulate long term experimental data sets consistently over a range of different land uses in a comparison of nine of the leading SOM models (Smith et al., 1997). Stage 1 of the project involved the evaluation and refinement of these models in order to assess and improve their performance in the conditions found in each case study area. This

Table 2
Case study areas considered in the GEFSOC project

Case study	Area (km^2)	Climate	Dominant soil types FAO (1988)
The Brazilian Amazon	>5,000,000	Humid, Up to 3000 (mm yr^{-1})	Ferralsols, Acrisols, Arenosols, Leptosols, Cambisols, Plinthosols, and Gleysols
The Indo-Gangetic Plains, India	467,000	Arid to humid, 300–1600 (mm yr^{-1})	Cambisols, Gleysols, Fluvisols, and Solonetz
Jordan	89,206	Arid to humid, 80% of the country <200 (mm yr^{-1})	Gypsisols, Calcisols, Solonchaks, Leptosols, and Cambisols
Kenya	582,646	Arid to humid, 150–2500 (mm–yr^{-1})	Solonetz, Cambisols, Luvisols, Regosols, Ferralsols, Planosols, Arenosols, Lixisols, Vertisols, and Nitisols

NB: Major soils are listed from largest to lowest extent, and all major groups listed cover >5% of the country/case study area. Data for India, however, are only for the IGP-region (and based on the IGP-simplifications) (>5% of IGP).

procedure is necessary as the application of unevaluated, unmodified temperate-region models to tropical conditions can lead to over/under estimations of SOC turnover (Gijsman et al., 1996). In order to do this, time series data sets, which had measured change in SOC, were collated in each of the case study regions. These included long term experimental data sets and land use chronosequences. The ability of the models to simulate these data sets was then evaluated (Cerri et al., 2007a; Bhattacharyya et al., 2007a; Kamoni et al., 2007a). Where necessary, modifications and refinements were made to the models (Easter et al., 2007). Scope for modification existed, as some of the crops grown in the case study areas had not been modelled before using either Century or RothC. Likewise, many of the soil types had not been modelled before.

- *Stage 2*: *Model input data*. Existing national and sub-national scale data sets of climate, historical and current land use, and land management were collated from a variety of sources and put into standard format. Soils data utilised existing Soil and Terrain (SOTER) databases, for three of the case study countries and a new SOTER was compiled for the Indian IGP. The SOTER databases were enhanced and adapted to enable use by the models (Batjes et al., 2007). Climate data came from grid based data, global data sets and point based data from national networks of meteorological stations and previous research projects. Land use and land use history data came from government statistical bulletins, research reports and global data sets. In addition, information on land management was collated, e.g. crop, forestry and pasture management practices specific to each case study area. The GEFSOC project used existing data sets from a variety of sources with the idea of consolidating fragmented data into an easily accessible format that could be used by a generic modelling system. The datasets produced will be useful for compilation of national inventories of GHGs, other research projects (related to SOC and soil fertility) and agricultural, biodiversity and land degradation assessment in addition to SOC stock change assessment.
- *Stage 3*: *SOM model/GIS linkage*. The third stage involved the development of the system to link the two dynamic SOM models and the IPCC model to spatial databases via a GIS system, and development of the GUI and the components to run the three assessment methods. The empirical IPCC method was included so that output from the dynamic RothC and Century components can immediately be compared with output from a standardised, default method. Further details are given in Easter et al. (2007).
- *Stage 4*: *Assessment of current SOC stocks*. The fourth stage was to assess current SOC stocks (for each case study area) using the GEFSOC Modelling System. This demanded both current and historical land use and land management information. Current land use was determined in each case study area for the most recent year possible, depending on data availability. Historical and current land use and land management information (such as crop type, crop rotation, pasture management, etc.) were assembled into sequences of management change over time. The proportion of a given area in a specific management time sequence was determined using expert knowledge and data obtained from the land use statistical reports collated during Stage 2. The GEFSOC system can generate output data at points in time determined by the user. Projections of the GEFSOC system for a base line year (1990) have been evaluated against independent results obtained with 'existing' techniques, as described in Bhattacharyya et al. (2007b), Al-Adamat et al. (2007), Cerri et al. (2007b) and Kamoni et al. (2007b).
- *Stage 5*: *Assessment of changes in SOC stocks*. The final stage was then to assess projected changes in SOC stocks under a range of plausible land use change scenarios for the target year 2030. In order to do this, the proportion of land that would change land use or land management between 2000 and 2030 was determined, in effect extending the work carried out in Stage 4. Inferences about possible land use/land management change were made from extrapolation of current trends, plans and policies outlined in government documents and predictions of change in crop production and cropped area made by the Food and Agriculture Organisation (FAO, 2002). GEFSOC system model runs were carried out from 7000 years before current land use (to derive a starting value for SOC) to 2030 and output taken for the years 1990, 2000 and 2030, giving an estimated current SOC stock for the year 2000 and projected SOC stock for 2030 (Al-Adamat et al., 2007; Bhattacharyya et al., 2007b; Cerri et al., 2007b; Kamoni et al., 2007b).

7. The GEFSOC system and future prospects for national and sub-national scale estimates

The GEFSOC Modelling System provides countries in tropical and arid areas (and other areas) with an improved method of producing SOC stocks and stock changes at the national and sub-national scale. It is the first national scale SOC stock assessment system that has been specifically tailored towards use in tropical and arid areas, to utilise a coupled SOM model/GIS system and to employ an easy to use GUI allowing the user to select/enter detailed soils, climate, land use and land management information. The system runs three assessment methodologies simultaneously at the national or sub-national scale and produces spatially explicit results in GIS format.

The system can, and has been used to, assess the effects of varying land use change scenarios on future SOC stock changes (Al-Adamat et al., 2007; Bhattacharyya et al., 2007b; Cerri et al., 2007b; Kamoni et al., 2007b), allowing areas with particular potential for C sequestration to be identified. This information will be useful for land use planners and policy makers when assessing the sustainability of proposed land management plans. It will also aid in the preparation of project proposals to gain credit for C storage, through schemes such as the Clean Development Mechanism (CDM).

The system can also be used to improve GHG emission inventories. The IPCC provides guidelines for estimating emissions and/or removals (sinks) for soil C from land use (agriculture and forestry) activities as part of national greenhouse gas inventories. The IPCC guidelines (IPCC, 2004) employ a multiple 'tier' approach, i.e.: (1) Tier 1 employs simple empirical models with default parameter values as supplied in the Guidelines, (2) Tier 2 uses the same model as in Tier 1 but with country supplied parameters (e.g. reference soil C stocks, emission and stock change factors), and (3) Tier 3 is defined as advanced inventory methods, typically employing process based models and/or inventory measurement networks. Countries are encouraged to use the highest Tier methods that are in line with country circumstances and capabilities, particularly for activities that represent 'key source/sink' categories.

The GEFSOC Modelling System provides the opportunity for developing countries to use an advanced (Tier 3) inventory methodology, using the two most widely used soil C simulation models available (Century and RothC), to improve estimates of land use related C emissions and/or sequestration. The GEFSOC system also provides estimates using the default Tier 1 approach, within the same software package. Further, if country specific stock change and emission factors are available, these can be entered into the database via the graphical user interface to construct a Tier 2 inventory. Hence countries can readily identify which land use activities and/or geographic areas within their country are potentially of most importance as a C source or sink. They can make comparisons between Tier 1 (and Tier 2) and Tier 3 based estimates and use the information to set priorities for collection of additional information to reduce uncertainties for key sources and sinks. The GEFSOC system is unique in providing multiple approaches for computing soil C emissions and removals for national greenhouse gas inventories. The system is freely available for download at http://www.nrel.colostate.edu/projects/gefsoc-uk.

Acknowledgments

The project *Assessment of SOC Stocks and Change at National Scale* was co-financed by the GEF (Project number GFL-2740-02-4381) with the UNEP acting as implementing agency and The University of Reading acting as the coordinating agency. It was carried out by a consortium of partners from Austria, Brazil, France, India, Jordan, Kenya, the Netherlands, the United Kingdom, and the USA with additional funding from a wide range of sponsors (see http://www.nrel.colostate.edu/projects/gefsoc-uk for details).

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