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The GEFSOC soil carbon modelling system: A tool for conducting regional-scale soil carbon inventories and assessing the impacts of land use change on soil carbon

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Abstract

The GEFSOC soil carbon modelling system was built to provide interdisciplinary teams of scientists, natural resource managers and policy analysts (who have the appropriate computing skills) with the necessary tools to conduct regional-scale soil carbon (C) inventories. It allows users to assess the effects of land use change on soil organic C (SOC) stocks, soil fertility and the potential for soil C sequestration. The tool was developed in conjunction with case-studies of land use and management impacts on SOC in Brazil, Jordan, Kenya and India, which represent a diversity of land use and land management patterns and are countries where sustaining soil organic matter and fertility for food security is an on-going problem. The tool was designed to run using two common desktop computers, connected via a local area network. It utilizes open-source software that is freely available. All new software and user interfaces developed for the tool are available in an open source environment allowing users to examine system details, suggest improvements or write additional modules to interface with the system. The tool incorporates three widely used models for estimating soil C dynamics: (1) the Century ecosystem model; (2) the RothC soil C decomposition model; and (3) the Intergovernmental Panel on Climate Change (IPCC) method for assessing soil C at regional scales. The tool interacts with a Soil and Terrain Digital Database (SOTER) built for the specific country or region the user intends to model. A demonstration of the tool and results from an assessment of land use change in a sample region of North America are presented.

Keywords: Soil organic carbon; Century model; RothC model; Land use change; IPCC method

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1. Introduction

Milne et al. (2007), describe the need for a scaleable and generic system for modelling soil C stocks and change rates at regional or country scales. This paper describes the technical and conceptual details behind the GEFSOC modelling system, which was built to meet that need.

The system was designed with the notion that an interdisciplinary team of experts will work cooperatively to assemble the input datasets required by the GEFSOC system, complete the modelling of soil C change in response to land use and management and evaluate the results. The system is based on a modelling system developed at the Natural Resource Ecology Laboratory (NREL) at Colorado State University to conduct regional and national soil C inventories (Paustian et al., 2002; EPA, 2006), but with substantial modifications to allow it to be used in more modest computing environments. The system was designed to meet the following criteria: (a) be scaleable to different geographic regions with diverse soils, climate and land use patterns, (b) utilize local expert knowledge on soils, climate, native vegetation and land use, (c) use affordable, off-the-shelf computer equipment, (d) use affordable, easily obtainable computer software or free software that may be downloaded from the internet or installed from a CD obtained from the NREL, (e) be utilized by scientists with a knowledge in scientific computing, using GIS and spreadsheet software, (f) be utilized by scientists with a minimum level of skill using the Redhat® LINUX operating system and (g) be a system in which all software and user interfaces would be released as open source under the GNU public license agreement.

The system provides estimates of soil C stocks at multiple time periods (for historic as well as future scenarios), using three well-recognized models and methods: (a) the Century general ecosystem model (Parton et al., 1988, 1992; Paustian et al., 1992), (b) the RothC soil C decomposition model (Jenkinson et al., 1992; Coleman and Jenkinson, 1995) and (c) the empirical Intergovernmental Panel on Climate Change (IPCC) method for assessing soil C stock changes at regional scales (IPCC, 2004).

The system requires a Soil and Terrain Digital Database (SOTER) (Van Engelen and Wen, 1995; Batjes, 2003; Batjes et al., 2007) that has been specifically constructed for the region or country the user intends to model. There are numerous SOTER databases available for many countries of the world (FAO et al., 1998a,b; FAO and ISRIC, 2000, 2003), with many new SOTER projects ongoing. There is a substantial published literature on Century and RothC and the IPCC method, as well as tutorials and reference manuals for all three models (Metherell et al., 1993; Coleman and Jenkinson, 1995; IPCC, 2004).

The objective of this paper is to present technical details of The GEFSOC modelling system and to demonstrate it's potential use by applying it to an example area of the USA.

2. System architecture

Full details of the system architecture, including hardware and software requirements, as well as tutorials and instructions for downloading and installing software are provided in Easter et al. (2005), available at http://www.nrel.colostate.edu/projects/gefsoc-uk/GEFSOC%20-SYSTEM.htm. Hence, only a brief overview of the system design and computing performance is given here.

The hardware and software necessary to operate the system are shown in Table 1 and Fig. 1. The modelling system was originally designed to run on two linked computers, although it is now programmed to work either on a single LINUX workstation/server, on loosely coupled clusters of LINUX workstations/servers with up to 15 processors, or on parallel processor clusters with up to 15 processors with single or multiple processors on each node.

Table 1
Software requirements of the GEFSOC modelling system

PC software required	LINUX software required
Microsoft® Access 2000 or Access 2003 (must be purchased)	Redhat® LINUX Fedora Core 2 (provided)
Microsoft® Excel (any version) or other spreadsheet software (must be downloaded or purchased)	Century Version 4 General Ecosystem Model (provided)
ESRI® Arcview or ArcGIS (or equivalent) and other GIS tools for assessing land use management (must be downloaded or purchased)	RothC Version 26.3 Soil Carbon Model (provided)
ActiveExperts® Network Communications Toolkit (provided)	PERL version 8.61 (provided)
MySQL® ODBC driver (provided)	MySQL® version 4.012 (provided)
Secure Shell Version 3.9 or later (provided)	PERL DBD and PERL DBI for MySQL® (provided)
Textpad® text file editor or equivalent (purchase and download), or Microsoft® Notepad (exists on all Windows installations)	GEFSOC Soil C Modelling System LINUX modules (provided)
GEFSOC Soil C Modelling System Access modules (provided)	

N.B.: Software components that are provided with the system download are noted as (provided). Software components that must be downloaded or purchased are noted.

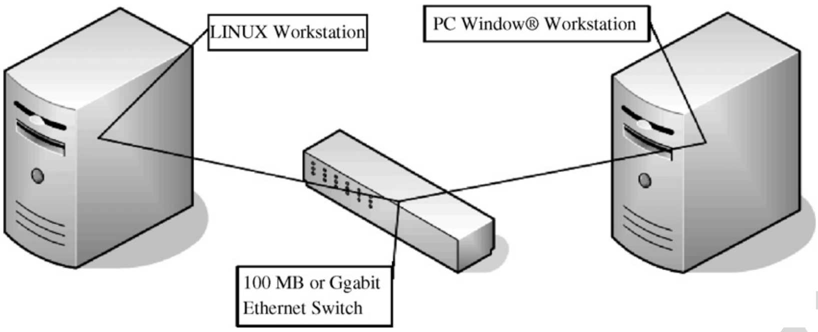

Fig. 1. Hardware required for the GEFSOC soil carbon modelling system. *N.B.*: The switch can be replaced with a single crossover cable.

The machines must be co-located to allow networking. Software installation is straightforward, with installation tutorials provided to guide users through the Windows® and LINUX software installations.

The equipment requirements are modest. During system development, the system was tested on a 400 MHz Pentium III desktop system with 128MB of RAM and a 200 MHz Pentium II laptop with 64MB of RAM. As a proof of concept, the LINUX portion of the modelling system worked seamlessly when scaled down to a single low-performance laptop or up to a high-performance Beowulf cluster with 18 processors.

The duration of model runs and post processing is proportional to the number and speed of the processors and memory available per processor, the complexity of the land use scenarios and the number of separate land use/climate/soils polygons or grid cells that are to be simulated. At the NREL, model runs were carried out on a parallel processor with nine dual-processor Athlon 1.67 GHz LINUX nodes with 2GB of RAM, connected using Gigabyte internet. Completing the model runs and post processing for the country of Jordan (Al-Adamat et al., 2007), with five land use polygons, an average of 28 management sequences per land use polygon, 13 climate polygons and 27 soil units required approximately 25 min of processor time on just one dual processor node for the model runs, and approximately 10 min for post processing. Conversely, for the Brazilian Amazon region (Cerri et al., 2007b), with 450 land use regions, 298 soil units, 450 climate polygons and 47 distinct management sequences per land use polygon, approximately 7.5 h was required for the model runs and 1 h for post processing. The time required to complete model runs is inversely proportional to the number of computers and processors available in the computing cluster.

3. The GEFSOC modelling system process

The steps required to complete a soil C inventory for a region or country with this system closely follow those described by Milne et al. (2007). For demonstration purposes, we constructed a simple example dataset from the Great Plains/Rocky Mountain ecotone in the state of Montana, in the Northern US (Fig. 2). The area is comprised of two main eco-regions or Major Land Resource Areas (MLRA), as defined by the US Department of Agriculture (Oman, 2002). MLRA 52, the Brown Glaciated Plain, is on the Northern Great Plains, with land use dominated by livestock grazing, hay and annual grain production. Soils are generally developed from alluvial deposits or loess. Mean annual temperature is about 11 °C, with annual precipitation totalling about 330 mm. The adjoining MLRA 46, the Northern Rocky Mountain Foothills, is in the Northern Rocky Mountains, an area dominated by timber production, livestock grazing and forest reserves, with a small amount of cropland. Soils are generally derived from alluvial or colluvial deposits and glacial till. Mean annual temperature is about 9 °C and annual precipitation is about 550 mm.

The use of empirical and simulation models for spatially distributed, regional estimates of C dynamics have been reported by a number of investigators (e.g. King et al., 1997; Falloon et al., 1998; Paustian et al., 1997; Ogle et al., 2003). As described by Ogle and Paustian (2005), the steps required to produce high quality regional estimates include model selection and evaluation, compilation of spatially and temporally distributed input data, assessment of uncertainties, model implementation and verification/validation of model results. We illustrate how the GEFSOC system can be applied to an example region in the Northern Great Plains.

Fig. 2. Location of an example study region, the ecotone of the Great Plains-Rocky Mountain Front of the Northern US. *N.B.*: The example study region shown in comparison to the rest of the United States.

3.1. Model selection and evaluation

Normally, when developing regional or national-level soil C inventories, one or more models are preliminarily selected for use. For example, many countries are currently using the IPCC default method, while several countries are developing new models or using existing soil C simulation models (Lokupitiya and Paustian, 2006). The GEFSOC tool is unique in that it integrates two of the most widely used soil C simulation models, Century and RothC, together with the IPCC empirical model. Thus to this extent, users automatically have a choice of models within the GEFSOC system.

While all three models have default parameterizations, each of the models have parameters that can be altered to better represent country or region specific conditions. For the IPCC model, this is referred to as a ‘Tier 2’ approach (i.e. an approach that determines reference C stocks and stock change factors using country-specific data) and procedures for doing so are described by IPCC (2004). For Century, and to some extent RothC, several parameters may be chosen to adapt the model to local conditions, e.g. pedotransfer functions governing water holding characteristics, background rates of N addition (i.e. through atmospheric deposition and native N fixation), temperature sensitivity of decomposition rates etc. Moreover, estimation of primary production and C inputs from plant residues are estimated using simple plant growth models that are designed to be calibrated for specific vegetation and/or crop varieties (Metherell et al., 1993). Hence, it is recommended that GEFSOC System users identify relevant agricultural or land use experiments from their region or country that can be used for region-specific parameterization. Ideally, these experiments should have data for primary production and/or crop yields and standing biomass (for forest and grassland) and measurements of soil C for the dominant vegetation types and land uses in the modelled region (or from areas with similar climate, land use and soils in other regions if this information is not available). Long-term field experiments with well-characterized management histories and repeated measurements over a decade or more, of crop yields or plant production and soil organic C to a depth of 20 or 30 cm are well suited for model evaluation (Paul et al., 1997; Smith et al., 2001). Examples of such field experimental data for the Montana demonstration region are shown in Figs. 3 and 4. Another common source of data are ‘paired-plot’ comparisons or chronosequences, which are often used to estimate changes in ecosystem C stocks due to land use change (e.g. Davidson and Ackerman, 1993). Even where soil C measurements are unavailable, data on primary production from field experiments and other sources (e.g. crop yield surveys, remote sensing) are invaluable for ensuring that estimates of net primary productivity and plant residue C inputs to soil are well represented. Smith et al. (1996a,b) published a useful tool (MODEVAL) for statistically evaluating model performance, based on work by Addiscott et al. (1995). Examples of model evaluation work from three of the GEFSOC case-study countries are given in other papers in this special issue (Bhattacharyya et al., 2007a; Cerri et al., 2007a; Kamoni et al., 2007a).

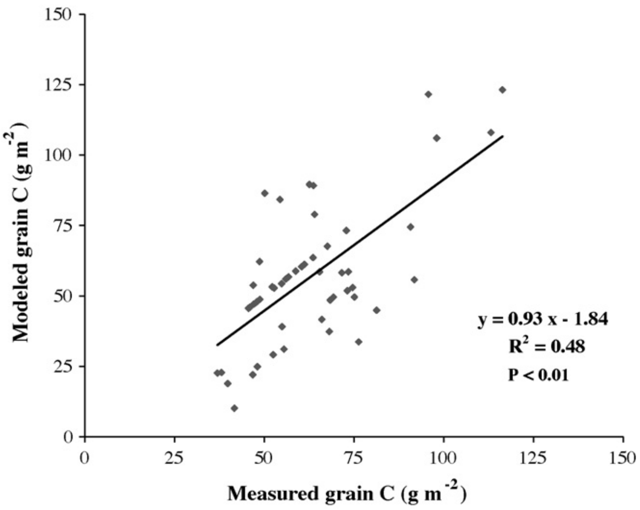

Fig. 3. Measured vs. Century modelled spring wheat grain yields for multiple sites across the Northern Great Plains of the US and Canada. *N.B.*: The data suggest that either total crop production or the crop harvest index parameters within the model should be modified slightly to more accurately model spring wheat production for the region. Data are from multiple sources.

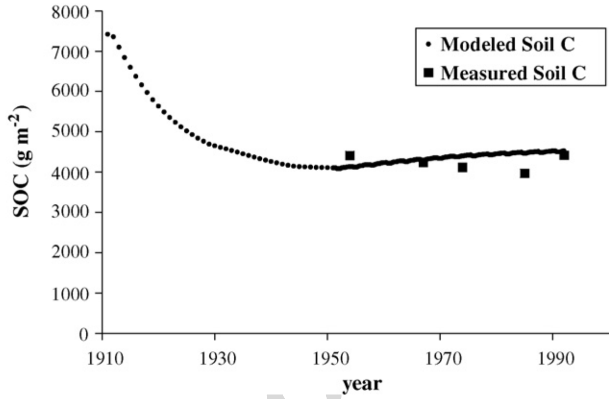

Fig. 4. Measured vs. modelled soil C in a fallow-spring wheat-spring wheat experiment with manure additions at Lethbridge, Saskatchewan. Data adapted from Larney et al. (1997).

3.2. Compilation of model input datasets

Spatially distributed data are often organized in geographic information systems (GIS) and such systems can be used to build most of the input datasets required by the GEFSOC modelling system. Land area can be subdivided into a regular grid pattern or irregular polygons. In the four case study countries, a combination of polygon-based coverages and grid-cell based coverages were used (Al-Adamat et al., 2007; Bhattacharyya et al., 2007b; Cerri et al., 2007b; Kamoni et al., 2007b). When applying the

GEFSOC system, five basic data coverages are required to build the datasets necessary for a regional simulation. These are described below.

3.2.1. Native vegetation

To initialize the soil C pools in the Century and RothC models (hereinafter referred to as ''the models''), a 'spin-up' procedure is used to estimate equilibrium conditions under native conditions, prior to significant human disturbance. Native vegetation types determine the parameters of the Century plant growth model used in the model spin-up. For each distinct class of native vegetation, a separate set of Century model events must be constructed. RothC does not simulate plant growth and residue inputs, therefore, the estimates generated by the Century plant growth submodel are used as driving variables in the RothC soil C calculations.

For the Montana demonstration region, two native vegetation types were included in the equilibrium model runs. For the eastern part of the region, MLRA 52, a mixed grass prairie, consisting of 75% cool season grasses and 25% warm season grasses, was simulated, including periodic low intensity grazing and a 7-year fire return interval. The western MRLA 46, was simulated as a pine-grassland savanna with a 30-year fire frequency. Potential native vegetation types for the MLRAs were taken from NRCS (2006).

3.2.2. Historic, recent, current and future land use/management

In order to produce a representation of current conditions, the influence of historical land use, up to 100 years before present, is simulated in the models (i.e. as a second phase in the model initialization process). Previous work has shown that a ca. 100-year historical land use representation is an adequate time period for the purposes of model initialization up to the start of the estimation time period (e.g. Gijsman et al., 1996; Gutmann et al., 2005; Parton et al., 1987). In general, the main objective of the modelling exercise is the estimation of recent (e.g. 20–30 years before current), current and future changes in ecosystem C stocks. The fulfilment of this objective should be kept in mind when the resolution and specificity of the land use and management data are chosen.

This GEFSOC system requires the user to assemble historic, recent, current and future time block sequences of management activities. The user must then define the area–proportion relationship between these sequences according to historic and/or predicted transition rates between land management systems as described later in this paper. A separate set of Century model events and IPCC management and input classes must be constructed in the modelling system database for each major type of land use/management for the historic, recent, current and future periods.

For the Montana demonstration region, land use histories were based on a broad, regional survey conducted by USDA's Natural Resource Conservation Service, as part of a separate effort involving assessment of historical land use and agricultural conservation practices (J. Brenner, pers. comm.). Time series estimates of the dominant land use and management practices within each region were collected through an interview process with local resource managers using techniques derived from more detailed county level land use surveys (Brenner et al., 2002). We chose to use this data source for two reasons: first, for its relative simplicity in demonstrating the operation of the GEFSOC system, and secondly, because it represents the type of data which could be acquired in many developing countries that may lack more formalized land resource inventory systems. The types of data collected included the dominant land use systems, time periods for conversion of native ecosystems to human use, and general time sequences for major changes in management practices (e.g. crop rotations, tillage regimes, fertilization practices, grazing rates) for cropland and grassland.

The time blocks specified in the survey data for Montana were 1891–1920, 1921–1950, 1951–1974, 1975–1994, 1995–2004 and 2005–2029. Land area totals over time, for cropland and grazing land, were estimated from land use survey data (USDA, 2006a; Paustian, unpublished data) and crop production statistics (USDA, 2006b). Relative weights for the dominant land uses and management practices for each time period, from the land use survey, were combined to estimate the land area associated with each management sequence. In MLRA 46, four forest management regimes were modelled, native unmanaged forest and managed forest with three disturbance regimes: clear cut, partial cut and stand-replacing fires. Six cropland scenarios, involving mixtures of small grains and alfalfa (*Medicago sativa*) hay, with three tillage regimes (conventional, reduced till and no-till), were simulated. In MLRA 52, eight combinations of small grains, alfalfa, irrigation and tillage systems were simulated, plus irrigated grassland hay and set-aside of cropland (i.e. Conservation Reserve Program) as unmanaged grassland. Three different grazing regimes were simulated on permanent pastures. In total, 59 unique 'chains' or management sequences, representing current and historical management histories, were modelled.

3.2.3. Climate

Climate data (either grid based, polygon based or point based) are needed to drive the models and the IPCC method. Typically, either a set of climate zones is defined as a separate spatial coverage or higher-resolution climate data is aggregated to correspond to another spatial unit, such as land use zones. For each climate zone, a table of monthly precipitation, maximum temperature and minimum temperature is constructed in a format described in Easter et al. (2005).

In the Montana example, mean climate data were constructed from 4 km^2 gridded values from the PRISM dataset (Daly et al., 1994) and averaged within the same polygons used for land use, with one major exception, the climate polygon for MLRA 52 was divided into two parts to better represent the east–west gradient in temperature and precipitation across the MLRA. In general, when constructing aggregate climate zones, if mean annual precipitation varies by more than 50 mm or mean annual temperature varies by more than 2 °C within climate polygons, users are advised to split the polygons into subunits to avoid a climate induced bias in the model run results. This 50 mm/2 °C threshold was determined by considering modelling results within temperate regions of North America and was established to eliminate aggregation bias of more than 5% in the modelled results (Paustian et al., 2001). Users should examine these threshold levels in the context of the soils, climate and crops or native vegetation they are modelling and consider changing them based on the degree of aggregation bias they decide is acceptable for their systems.

3.2.4. Soils

The IPCC method requires that soils be classified according to texture and/or general physical/chemical properties and the models require soil texture and hydric condition as inputs. These data are derived from a SOTER database for the modelling region and the associated SOTER GIS coverages. If the user has to create a new SOTER database for the region to be modelled, the GEFSOC system does not require the landuse and climate components in the SOTER to be completed. Only the soils information in the SOTER database is used by the current version of the GEFSOC system.

For the Montana example, a SOTER database was constructed from the STATSGO digital database of soil associations, which maps soil type at a scale of 1:250,000 (SCS, 1994), using a soil taxonomy transfer rule-based approach developed for the GEFSOC Project (Batjes, 2003).

3.2.5. Latitude

Latitude of the land units is used, along with climate data, to estimate potential evapotranspiration in the models. Users may use the mean latitude of the land use polygons to fulfil this requirement. However, to enhance precision, users may also wish to use the features within their GIS to calculate the

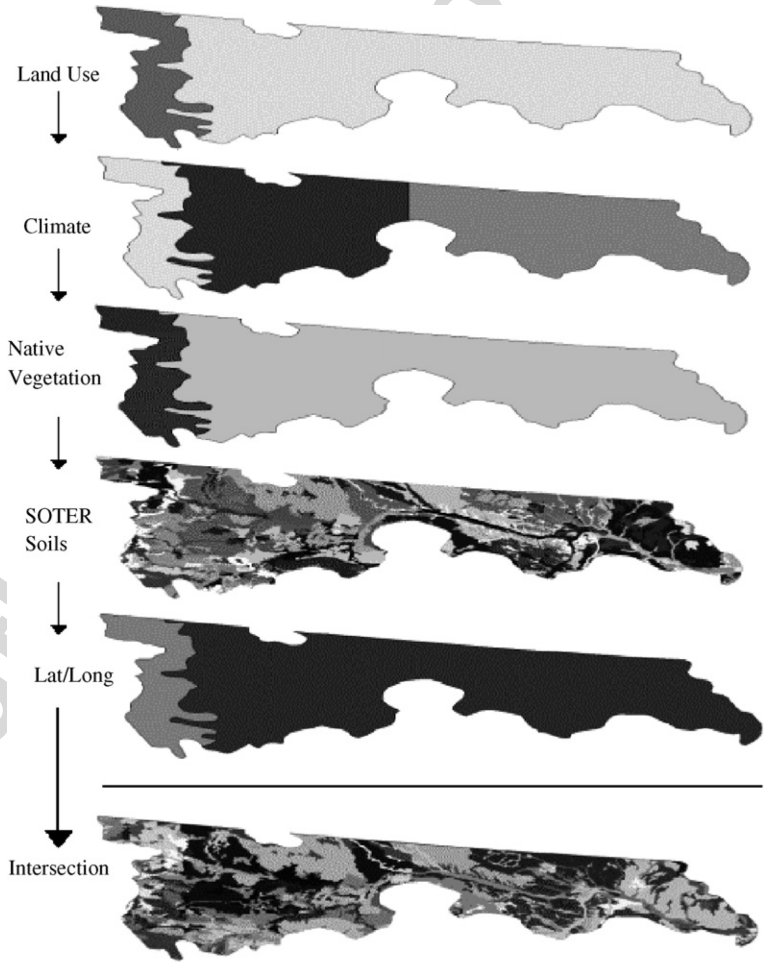

Fig. 5. Diagrammatic representation of the GIS coverages from five data classes being overlain. *N.B.*: The overlain coverages are used to produce a "run table" with the unique attributes of each coverage tied to the sub-polygons intersections within the model area.

latitude of the intersecting sub-polygon regions. This avoids creation of a separate coverage or addition of another data field to the land use coverage.

3.3. Linkage of GIS coverages and input datasets

Once the input datasets are constructed, there are four major steps that must be accomplished prior to initiating the model runs. The first is to construct (within the GIS software) a ''run table'', which is the unique intersection of the GIS data layers described above and depicted in Fig. 5.

These data are ''pasted'' into the model input database via a user interface as described by Easter et al. (2005). The second step is to paste the climate data table (described above) into the climate table within the GEFSOC modelling system interface. The third step is to construct, within the modelling system Interface, the Century model crops, rotations and histories associated with native vegetation, historic, recent, current and future land use. The fourth step is to construct management sequence diagrams for each of the distinct land uses within each of the distinct land use polygons (or grid cells) for the entire modelling period. These sequences detail the land use and management activities for each land unit. The specific details associated with each step are described in Easter et al. (2005).

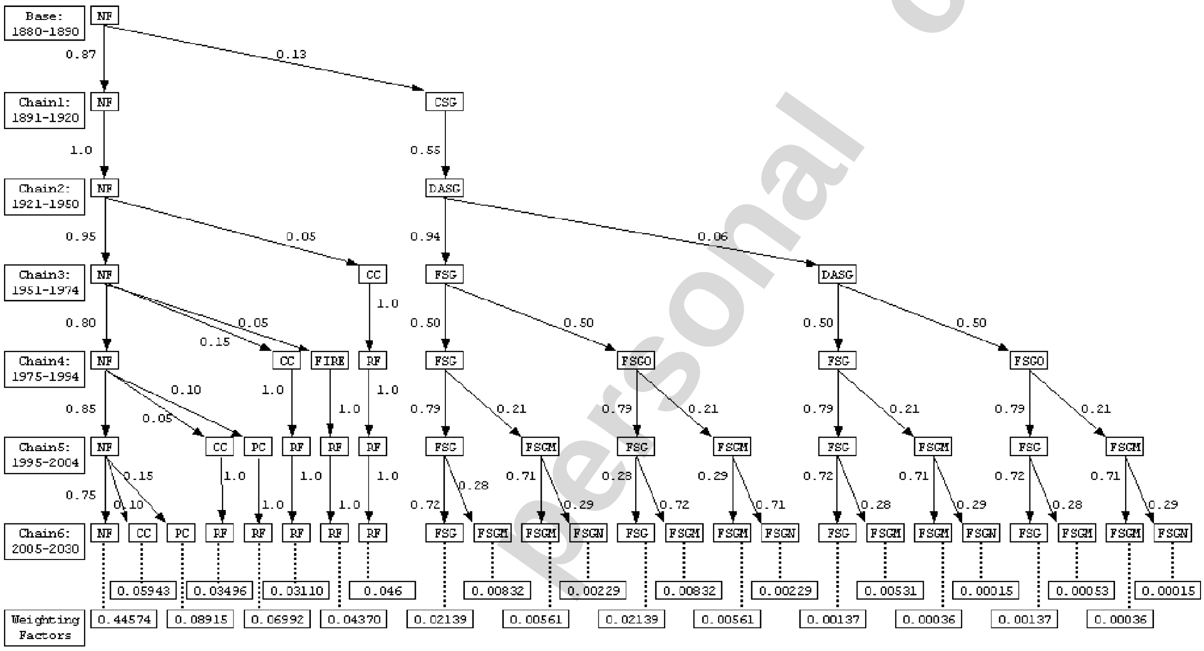

Fig. 6. Management sequence diagram for Major Land Resource Area 46. *N.B.*: NF, native forest; CC, clear cut tree removal; PC, partial cut tree removal; FIRE, stand-replacing fire; RF, regenerating forest; CSG, continuous small grains; DASG, dryland alfalfa-small grain; FSG, fallow-small grain (conventional tillage); FSGO, fallow-small grain-oilseed; FSGM, fallow-small grain (minimum tillage); FSGN, fallow-small grain (no tillage). Land management system descriptions and transition rate data are from Paustian et al. (in preparation).

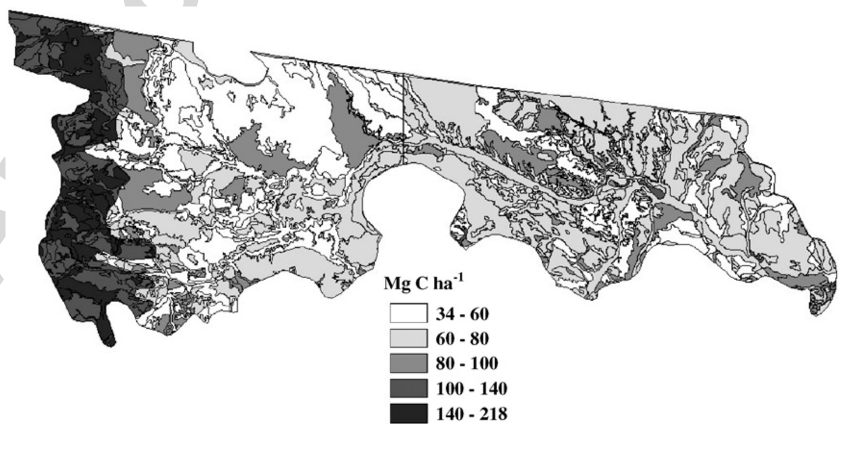

Fig. 7. Soil C stocks predicted by the Century model in an example area in Montana, plotted by the intersection of soil type, land use, native vegetation and climate region.

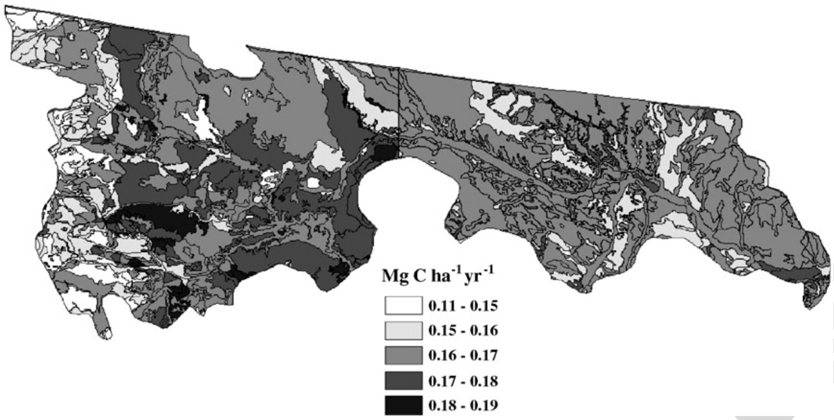

Fig. 8. Soil C change rates predicted by the Century model in an example area in Montana in no-tillage fallow-small grain rotations, plotted by the intersection of soil type, land use, native vegetation and climate region.

A management sequence diagram for the example from MLRA 46, in the western part of the region, is shown in Fig. 6. Within each management sequence diagram, the relative area associated with each transition is shown. For example, in the first transition sequence from 1880–1890 to 1891–1920, 87% of the land area remains as native forest and 13% is converted from native forest to continuous small grain production. Similar transition rates are assigned to each transition sequence in the diagram. The area-weighting factor associated with each management sequence chain is calculated by multiplying all transition factors within each distinct management sequence chain. The sum of all of the weighting factors must be 1.0 (indicating 100% of the original area has been accounted for). These data are used to 'area–weight' the modelled soil C values produced by the modelling system.

Each link in the management sequence chain must have a unique Century model cropping history defined within the modelling system database. Users link the chains together and associate the weighting factor with each chain of crop histories within the modelling system interface.

3.4. Assessment of soil C stocks

Before initiating the model runs, users create (via the modelling system interface) a set of input files required by the modelling system. The modelling system interface performs a set of error-checking routines, notifying the user of any errors in the input datasets. After correcting any errors, the user initiates the model runs on the LINUX computer(s) and is notified when the model runs are completed. The Century and RothC model runs are accomplished simultaneously via one process and the IPCC method runs are completed via a separate process.

The models generate large amounts of output data. A single regional model run set of 50,000–100,000 individual runs requires several gigabytes of storage for the raw data generated by the models. To reduce the size of the dataset, whilst still generating meaningful results for users, the modelling system stores the output as a continuous piecewise linear fit between user-defined breakpoints. The advantage of this approach is that trends are directly apparent to the user and both the accuracy of the fit and the storage requirements can be controlled by the number of

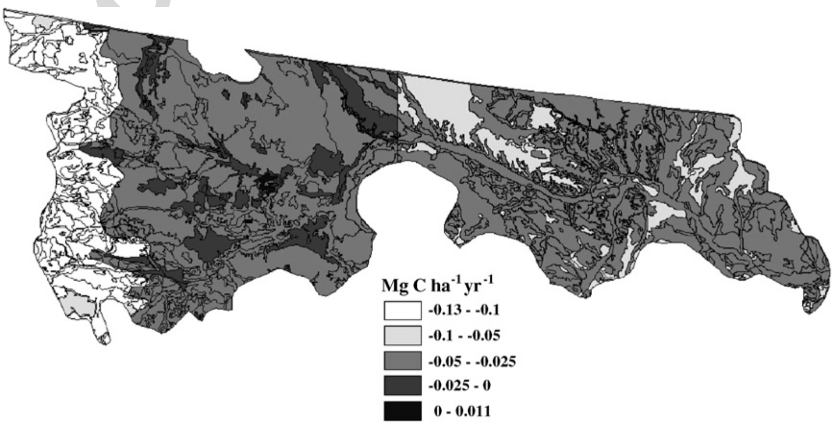

Fig. 9. Soil C change rates predicted by the RothC model in an example area in Montana in conventional-tillage fallow-small grain rotations, plotted by the intersection of soil type, land use, native vegetation and climate region.

Table 2
Predicted soil carbon change rates estimated using the IPCC method for the two Major Land Resource Areas (MLRAs) in an example region in Montana, USA

Land Mgmt Unit	Century (Mg ha^{-1} year^{-1}) (top 20 cm)		RothC (Mg ha^{-1} year^{-1}) (top 20 cm)		IPCC (Mg ha^{-1} year^{-1}) (top 30 cm)	
	1995–2004	2005–2030	1995–2004	2005–2030	1995–2004	2005–2030
MLRA 46	0.039	0.004	0.037	0.008	0.003	0.001
MLRA 52	0.044	0.028	0.002	−0.014	0.039	0.015

breakpoints specified by the user. The user defines the years for which soil C data are needed in the output dataset and any intermediate breakpoints. The modelling system calculates the intercept, slope and R^2 statistic for each time interval for the primary output variables, i.e. Century soil C, RothC soil C, Century above and below-ground production, Century C inputs and Century grain yields. IPCC change rates and stock values are calculated for the same time blocks. The IPCC model classifies change rates over 20-year time periods. These are extrapolated to the time blocks specified by the user.

Examples of the types of results users can generate from the model runs are shown in Figs. 7–9 and Table 2 for the example region in Montana.

3.5. Uncertainty analysis and validation/verification

As mentioned above, the estimation of uncertainty associated with soil C inventories is a topic that is receiving increasing attention, particularly when estimates are directly tied to governmental policies and decision-making. Widely used uncertainty estimators range from standard error-propagation techniques, for simple empirical models, to more computationally-intensive numerical approaches, such as Monte Carlo techniques (IPCC, 2004; Ogle and Paustian, 2005).

While there are no automatic, built-in functions for uncertainty analysis in the GEFSOC system, the database structures and execution control programs in the system are well-suited for the application of Monte Carlo techniques for deriving uncertainties in model estimates associated with uncertainties in the management and land use variables and other input data, including soil and climate attributes. For example, if probability distributions for input variables are available, e.g. for fertilizer application rates, these probabilities can be propagated as a suite of management event files with varying fertilizer rates based on the mean and variance of estimated fertilizer inputs. A similar approach can be used for tillage management, manure application or other management variables with defined uncertainties.

A disadvantage with the current GEFSOC system is that this approach would be difficult to implement with a large number of climate–soil–management combinations, such as in the Brazilian case study (Cerri et al., 2007b). A future modification of the GEFSOC system could include adding the capability to initiate Monte Carlo analyses by run-time alterations of the management event files based on specified probability distribution functions for key management inputs variables, as has been recently implemented in the US national soil C inventory (EPA, 2006).

Model verification and validation are final steps in model-based inventories, to identify biases and necessary modifications in the modelling process (Ogle and Paustian, 2005). The approaches and data sources for verification/validation are similar to those outlined earlier for model selection and evaluation, with the exception that the data must be independent from data used in model parameterization or calibration. Hence additional data in the form of traditional field experiments, chronosequences, flux tower estimates of ecosystem C balance, productivity estimates from crop yield surveys or remote sensing, are possible sources of data for validation purposes. In practice, however, rigorous validation of regionalized soil C estimates is often problematic, particularly in developing countries, due to limited data. In many cases available data is sparse for even the initial model evaluation and parameterization steps. No examples of model validation are given in the Montana demonstration analysis, however, see Ogle and Paustian (2005) for further discussion within the context of soil C inventories.

4. Results and discussion

The model analysis suggests that, overall, soil C in the study region is either relatively stable or increasing (Table 2). However, relative differences between the different models in the GEFSOC system were substantial, particularly when the simulation approaches were compared with output from the IPCC method. The estimate made using RothC was about 30% lower than that made using Century, while the IPCC method yielded a predicted soil C increase that was 6–10 times greater than estimated using the simulation approach. For the entire study region, the simulated SOC change rates in 2000 were estimated at 0.0026 Tg C year^{-1} (Century) and 0.0006 Tg C year^{-1} (RothC) compared to 0.0027 Tg C year^{-1} obtained using the IPCC method.

For comparison, results have been generated for the same region, as part of the US national greenhouse gas inventory (EPA, 2006; K. Paustian, unpublished data). A Century model-based method utilizing land use information from the US National Resources Inventory (NRI) for the period 1995–1999 yielded a gain of 0.21 Tg C year^{-1}. Whereas both the NRI-based inventory and GEFSOC use the Century model at their core, the NRI-based approach in the US inventory used a fundamentally different underlying structure to develop the land-use scenarios. Land use in the NRI-based approach was derived using a point-based inventory with detailed information reported for individual points since 1979. In contrast, the management sequences and land use transitions used to drive the model runs in the GEFSOC modelling system were based upon more coarse-resolution land use survey data, as this is more representative of the type of information available in many developing countries.

A more detailed examination of the results provides insights into some of the differences between results from the two simulation models and the IPCC method incorporated in the GEFSOC system. One reason why the IPCC method predicted different stock change rates to the modelling methods, could be that the Tier 1 (global default) reference C stocks and stock change factors are not entirely representative of conditions in the study region. For example, the IPCC method predicts relatively large soil C stock changes for conversion from conventional to no-till systems in dry, temperate regions (+10% over 20 years) relative to Century (+4% over 20 years) and RothC (approximately no change). The difference in stock change estimates between Century and RothC, in this case, is expected, as Century specifically simulates differences in tillage intensity and its impact on soil C whereas RothC does not. In addition, the modelling scenario we applied included a moderate decrease in grazing intensity on grazed lands within MLRA 46, to reflect grazing policy in the region. The IPCC method applies a 5% increase over 20 years in soil C on grazed lands that transition from moderately degraded to non-degraded, whereas both Century and RothC predict effectively no change rate in soil C on grazed lands. The IPCC method acknowledges the inherently high uncertainty of the Tier 1 defaults and recommends that region-specific factors (i.e. a Tier 2 approach) should be used, if data are available (IPCC, 2004).

On the other hand, comparing the Century-based results from the GEFSOC exercise with the US soil GHG inventory estimates, suggests that, whereas both the inventory and GEFSOC implementation predict modest increases in soil C in the study region, the GEFSOC implementation may underestimate those soil C accumulation rates. As described above, the Montana demonstration analysis uses a simplified representation of land use and management activity data derived from low-resolution survey data, whereas the US inventory analysis uses detailed inventory data from NRI, as described above. The roughly three-fold higher C accumulation rates for the same region in the US inventory compared to Century-based GEFSOC results are primarily due to differences in input data, particularly land use and management information, as Century is used in both analyses for simulating soil C dynamics.

Further analysis of the differences between the model outputs produced by the GEFSOC system, and a precise attribution of those differences to input sensitivities or differences in model assumptions and/or parameterizations, are beyond the scope of this paper. More detailed model evaluations and comparisons of results, for the actual implementation of the GEFSOC modelling system in the four case study countries, are provided by Al-Adamat et al. (2007), Bhattacharyya et al. (2007a), Cerri et al. (2007a) and Kamoni et al. (2007a). However, the results for simple demonstration regions (such as the region discussed in this paper) do illustrate some of the challenges in interpreting, verifying and validating regional-level estimates of soil C dynamics. The GEFSOC system, by incorporating three different models that utilize a common set of input data, encourages comparison of different results and a more thorough examination of the assumptions and data that make up the analysis. In climate change research, the coordinated use of multiple models for climate predictions and emission scenarios is now a standard means by which to provide information to policy- and decision makers.

5. Conclusion

During its development, the GEFSOC Soil C modelling system was used in a variety of areas including geographic sub-regions (such as the Indian portion of the Indo-Gangetic Plains and on a much larger scale the Brazilian Amazon) and for entire countries (Jordan and Kenya). A basic modelling system may be assembled for US $2000–4000 and it may also be implemented on large parallel processing clusters costing much more. The software is all either freely available or is widely available at a nominal cost. Users with moderate computing skills have proven their ability to learn how to use and parameterize the models, assemble the datasets, build the Century and RothC model and IPCC method inputs, execute the model runs and interpret the model run results.

Several important lessons were learned during the development and review of the GEFSOC modelling system. First and foremost, it must be emphasized that the availability of an efficient modelling system does not guarantee the production of accurate or meaningful results. As with all modelling approaches, the model output is dependent upon accurate model parameterizations and the quality of input datasets. It is important that an interdisciplinary team of local or regional experts in soils, land use and management be involved in creating accurate model input parameters and input datasets. The workload associated with assembling the input datasets and characterizing land use systems and management sequences is substantial. The modelling system method described by Milne et al. (2007) will likely take several months for a disciplined and organized team to complete. Any errors or inconsistencies in the input datasets will propagate through the model runs, leading to erratic or erroneous results and this must be recognized and corrected by the users. We estimate that, as a general rule of thumb, approximately 70% of the effort spent during the exercise will be in parameterizing the models based upon regional experiments, analyzing land use patterns, assembling land use statistics, compiling climate data and building a SOTER database from local soils maps (if a complete SOTER database does not already exist for the model region). Approximately 15–20% of the time will be spent creating the input GIS coverages, working with the modelling system interface, building Century land use histories, creating input tables and 'debugging' inconsistencies in the input datasets. The remaining time will be spent in an iterative process of running the modelling system, correcting and refining input errors, re-running alternative land use scenarios and interpreting results. As such, we recommend that users complete the model evaluation process and assemble input datasets before committing resources to purchase the LINUX node(s) and a networking switch.

For users of the GEFSOC system we particularly emphasize the importance of learning the Century and RothC models and the IPCC method. Users must understand how the input parameters may influence model outputs and how to structure the sequence of land use/management events. Evaluating regional land use or agricultural experiments against model performance is invaluable in assuring meaningful model results.

During the development of this system, a large number of suggestions for additional features to improve the modelling system were made by scientists in the case-study countries. Most have been included, however a small number are still in development. They include the following:

- The use of actual past weather datasets rather than mean climate data in model scenarios.
- The inclusion of climate change scenarios.
- A graphical user interface that allows users to initiate testing and model runs from the Windows machine rather than running them from the LINUX command line.

These improvements are all in process by staff at the Natural Resource Ecology Laboratory.

The GEFSOC modelling system was specifically designed to be released in an open source environment. All software and user interfaces written for the modelling system are released under the GNU public license agreement (http://www.gnu.org/copyleft/gpl.html). User group and discussion lists are available from the GEFSOC project web page (http://www.nrel.colostate.edu/projects/gefsoc-uk/).

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