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Short communication

SOCRATES—A simple model for predicting long-term changes in soil organic carbon in terrestrial ecosystems

Peter R. Grace [a,b,*], Jeffrey N. Ladd [c], G. Philip Robertson [b,d], Stuart H. Gage [e]

[a] School of Natural Resource Sciences, Queensland University of Technology, Brisbane, Qld 4060, Australia
[b] W.K. Kellogg Biological Station, Michigan State University, Hickory Corners, MI 49060, USA
[c] 6 Blackwood Avenue, Blackwood, SA 5051, Australia
[d] Department of Crop and Soil Science, Michigan State University, East Lansing, MI 48824, USA
[e] Department of Entomology and Computational Ecology and Visualization Laboratory, Michigan State University, East Lansing, MI 48824, USA

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Abstract

The maintenance of soil organic carbon (SOC) in terrestrial ecosystems is critical for long-term productivity. Simulation models of SOC dynamics are valuable tools in predicting the impacts of climate on carbon storage and developing management strategies for the mitigation of greenhouse gas emissions, however, their utility is generally reduced due to need for specific data. The SOCRATES model is a simple process based representation of soil SOC dynamics in terrestrial ecosystems, which requires minimal data inputs and specifically designed to examine the impact of land use and land use change on soil carbon storage. SOCRATES was successful in predicting SOC change at eighteen long-term crop, pasture and forestry trials from North America, Europe and Australasia. These trials ranged from 8 to 86 years in duration, over a wide range of climates and soil types with annual changes in SOC ranging from −3.0 to 4.2%.

Keywords: Soil organic carbon; Simulation; SOCRATES

The mass and long residence time of soil organic matter in the terrestrial environment make it a major component of the global carbon cycle (Post et al., 1990). Organic matter has a beneficial influence on the fertility and the physical properties of soil, directly contributing to productivity and soil conservation (Jenkinson, 1991).

The amount of carbon stored in soils is determined by the balance between primary productivity of the vegetation and associated litter inputs and the decomposition of native soil organic matter. Organic carbon levels in soils are therefore slow in responding to change. As a result, there is no easy way to experimentally determine if management practices will sustain environmental quality in the longer term (Rasmussen and Parton, 1994). With CO_2 emissions from fossil fuel combustion increasing globally by over 116 million tonnes C per annum (Marland et al., 2003), there is a growing interest in the use of management strategies that promote carbon sequestration in soils and thus reduce the net emission of atmospheric CO_2 and other greenhouse gases (Lal et al., 1998). Simulation models offer the time-saving prospect of testing and extending the application of experimental results on management responses to many sites (Rasmussen et al., 1998).

The influence of temperature and moisture on SOC dynamics is relatively well understood and simulation models have been successful in mimicking the processes and interactions which influence SOC cycling (Coleman et al., 1997; Franko et al., 1997; Kelly et al., 1997; Molina et al., 1997). SOCRATES, or Soil Organic Carbon Reserves And Transformations in EcoSystems, is a process based simulation model designed to estimate changes in topsoil SOC with a minimum dataset set of soil, climate and biological inputs. The main considerations in the development of SOCRATES were that it be based on generic concepts of carbon cycling and biogeochemistry, as well as being easy to use and widely applicable. It would also not require detailed fractionations of carbon pools as inputs. SOCRATES uses a weekly time step, however, the minimum driving variables are annual precipitation (mm), mean annual temperature (°C), soil clay content (%) or CEC (mmol kg^{-1}), initial soil organic C (%) and bulk

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* Corresponding author. Address: School of Natural Resource Sciences, Queensland University of Technology, Brisbane, Qld 4060, Australia. Tel.: +61 7 38642610; fax: +61 7 38642324.
E-mail address: pr.grace@qut.edu.au (P.R. Grace).

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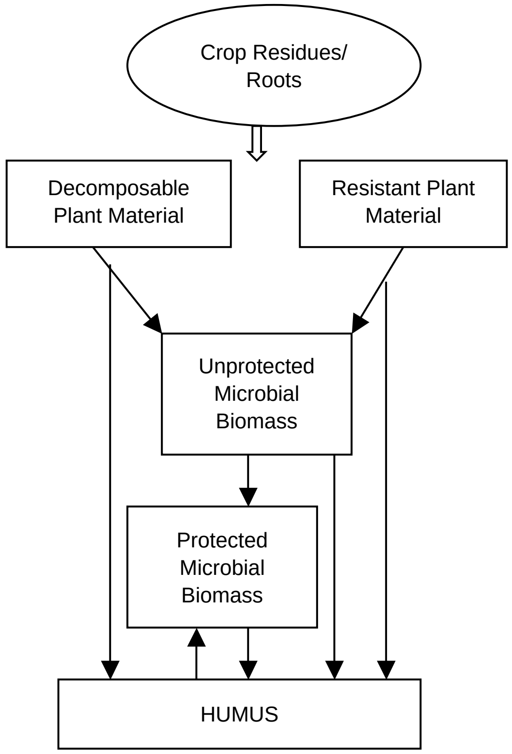

Fig. 1. Compartments and carbon transfers within the SOCRATES model.

density (g cm^3). A value of 1.3 g cm^3 is assumed for bulk density if that information is not available. Monthly climate values can be input if desired.

The carbon model consists of five compartments (Fig. 1) which undergo first-order decomposition in response to temperature and moisture. All plant material can be divided into decomposable (DPM) and resistant (RPM) components based on the conceptual fractions initially described by Jenkinson (1990). The respective DPM/RPM ratios for the litter produced from a terrestrial ecosystems are the same as those used by Jenkinson (1991) and are outlined in Table 1. The soil components consist of microbial biomass and humus, with the microbial fraction differentiated into a transient unprotected fraction (which is only involved in the initial stage of crop residue decomposition) and a protected fraction that is actively involved in the decomposition of native humus and subsequent microbial metabolites (Ladd et al., 1995). When initializing the model, it is only necessary to supply an initial SOC value, with 2% of the total SOC store considered to be protected microbial biomass and the remaining 98% defined as stable humus.

The decomposition process in SOCRATES produces humus, microbial materials and carbon dioxide in proportions which are dependent on the CEC of the soil (Fig. 2). The apportioning of C flows to the microbial biomass, humus and carbon dioxide, and the specific decay rates for each component of the model were calibrated using ^{14}C laboratory incubation data of Amato and Ladd (1992) and Ladd et al. (1995). For example, in a heavy clay soil with a CEC of 250 mmol kg^{-1}, 44% of the organic carbon undergoing decomposition from any of the fractions will be retained in the soil matrix at that time, with the remaining 56% being respired as CO_2. Three percent (a constant proportion) of the organic products are destined for the humus pool, with the remaining 41% transferred to the protected microbial biomass pool.

The first order decay rate constants used in the model (based on optimal moisture conditions at 25 °C) are 0.84, 0.06, 0.055 and 0.0009 w^{-1} for DPM, RPM, protected microbial biomass and stable organic matter, respectively. The decay rate of the transient unprotected microbial biomass is 0.95 d^{-1} and decomposition of this pool is simulated at a daily time-step to facilitate its rapid turnover. The first order decay rates are modified using multiplicative temperature (TF) and moisture (MF) factors. The effect of temperature on decomposition is based on a Q_{10} relationship of 2.0 (Eq. (1)) with T representing mean annual air temperature (°C)

$$\mathrm{TF} = 0.177\exp(0.069T). \tag{1}$$

Skjemstad and Janik (1996); Izaurralde et al. (2001) reported the accuracy of an earlier version of SOCRATES (Grace and Ladd, 1995) in simulating changes in SOC in agroecosystems. Izaurralde et al. (2001) found it to be superior to both the CENTURY (Parton and Rasmussen, 1994) and RothC-26.3 (Coleman et al., 1997) models (amongst others) for predicting long-term SOC change in arable and rangeland soils of the Canadian prairies. Oades (1995) demonstrated the versatility of the SOCRATES approach in simulating carbon change in tropical soils of north-east Australia.

In the original model, the MF was simply a defined value based on the vegetation type. To broaden the range of terrestrial ecosystems that could be simulated, we modified SOCRATES in two ways. Firstly, we incorporated an empirical MF (Eq. (2)),

Table 1
Parameters used in to partition net primary productivity for major land uses in the SOCRATES soil carbon model

Land use	Partition coefficient				Life span (year)				DPM/ RPM[a]	Roots[b]
	Leaf	Branch	Stem	Root	Leaf	Branch	Stem	Root		
Forest	0.3	0.2	0.3	0.2	2	10	60	10	0.2	0.25
Grassland	0.6	0.0	0.0	0.4	1	–	–	1	0.4	0.35
Arable	0.55	0.0	0.0	0.2	1	–	–	1	0.59	0.33
Shrubland	0.5	0.1	0.1	0.3	1	10	50	2	0.4	0.31

[a] Ratio of decomposable to resistant plant material as litter.

[b] Proportion of total roots in top 10 cm of soil.

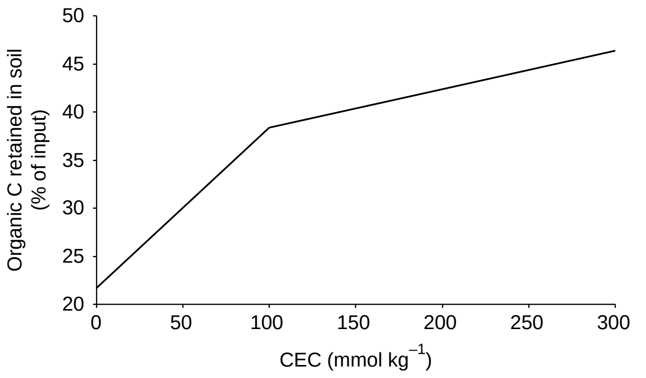

Fig. 2. Influence of cation exchange capacity (CEC) on retention of organic carbon within the soil matrix as simulated in the SOCRATES model.

$$\mathrm{MF} = 0.0598P^{0.279} \tag{2}$$

where P is mean annual precipitation (mm). We then included a simple net primary productivity (NPP) calculator (Lieth, 1975) to provide an estimate of carbon inputs into the soil. The latter is based on either the mean annual temperature T (°C) or average annual precipitation P (mm). Explicitly, the minimum value of Eqs. (3) and (4) is utilized

$$\mathrm{NPP}_T = \frac{3000}{(1 + \mathrm{e}^{1.315-0.0119T})} \tag{3}$$

$$\mathrm{NPP}_P = 3000(1 - e^{-000664P}). \tag{4}$$

Leith's Miami model was originally derived from 52 locations around the globe and whilst we recognise the shortcomings of its simplicity, we agree with Pittock and Nix (1986) that it has an advantage over site-specific regressions in that it is valid over a range of climates.

We used the same NPP partitioning constants and average life spans for biomass and litter production for the forest, grassland, shrub and arable (cropping) categories (Table 1) as outlined in Polglase and Wang (1992), except for arable ecosystems in which we reduced the leaf partitioning coefficient from 0.8 to 0.55 to account for the removal of harvested product (i.e. 25% of NPP). As we are only simulating SOC dynamics in the top 10 cm, annual root production in this layer was allocated according to Jackson et al. (1996). The C density of each plant component at steady state (B) is estimated using Eq. (5).

$$B = \mathrm{NPP}_p Y \tag{5}$$

where NPP is annual NPP (from Eqs. (3) or (4)), p is the partitioning coefficient for each of the plant components and Y is the average life span (in years), for the component (Table 1). The annual litter C input (L) for each plant component is then estimated by Eq. (6)

$$L = \frac{1}{Y}B. \tag{6}$$

Structurally, the carbon pools within SOCRATES, CENTURY and RothC models have similarities, however, only the DPM and RPM pools can be directly compared in terms of their decomposability. At 25 °C and at optimum moisture conditions, the weekly decay constants for DPM are RPM are 0.29 and 0.02 for SOCRATES, 0.26 and 0.07 for CENTURY (Parton et al., 1987), and 0.73 and 0.02 for RothC.

To test the model's capacity to predict SOC change with respect to the combined effect of temperature and moisture on decomposition and a generic NPP calculator, we compared SOCRATES simulations against observed SOC data from 18 long-term trials from North America, Europe and Australia where SOC and ancillary climate and soil data had been monitored. This data included experiments ranging from 8 to 86 years in duration, with a wide range in mean annual temperatures (5–17 °C) and precipitation (400–1200 mm), soil types (cation exchange capacity 70–270 mm kg^{-1}) and terrestrial ecosystems, including pastures, cropping, as well as a number of afforested sites selected from the compilation of Paul et al. (2002). Average annual changes in soil organic carbon stocks ranged from −3% (Gifford and Barrett, 1999) in pasture to forest conversion to +4.2% (Heenan et al., 1995) in cereal cropping systems. In the simulations all biomass (except grain in the case of crops) was preserved within the system.

The observed versus simulated SOC outputs for the 18 sites are depicted in Fig. 3. The r^2 with all sites included in the analysis is 0.96 ($P < 0.001$) with all sites closely aligned with the 1:1 line. Removal of site 5 from the regression equation reduced the r^2 to 0.81, but did not affect the very highly

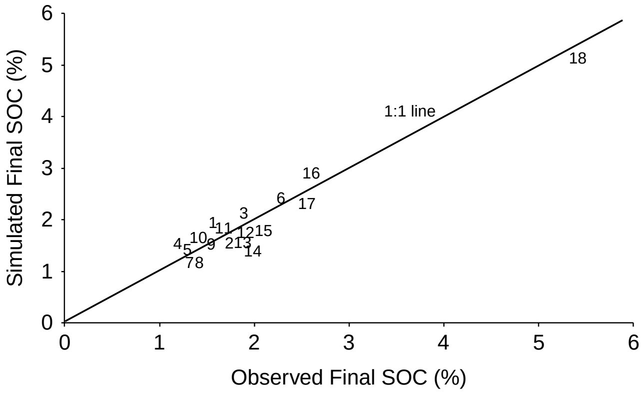

Fig. 3. Comparison of observed and simulated SOC in the surface 10 cm in agricultural (sites 1–6) and afforested sites (7–18) from a global dataset using the SOCRATES model to simulate long-term SOC dynamics in response to climate, soil type and litter management. The number in parentheses after the country name indicates the total number of years simulated. Factors for converting 0–15, 0–20 and 0–30 cm data to 0–10 cm were 75, 60 and 43%, respectively. 1 = Illinois, US (86), Darmody and Peck (1997); 2 = Lethbridge, CA (80), Janzen et al. (1997); 3 = Saginaw, US (19), Christensen (1997); 4 = Wagga Wagga, AU, Heenan et al. (1995) (13); 5 = Missouri + straw, US (33), Buyanovsky et al. (1997); 6 = Arlington, US (25), Vanotti et al. (1997); 7 = Germany (10), Jug et al. (1999); 8 = Germany (10), Jug et al. (1999); 9 = Vermont, US (50), Schiffman and Johnson (1989); 10 = ACT, AU (17), Gifford (2000); 11 = Tumut, AU (8), Gifford and Barrett (1999); 12 = Sweden (20), Alriksson et al. (1995); 13 = Georgia, US (70), Huntington (1995); 14 = Minnesota, US (60), Zak et al. (1990); 15 = Rothamsted-Geescroft, UK (100); Jenkinson et al. (1992); 16 = New Zealand (20); Giddens et al. (1997); 17 = Western Australia (11), Grove et al. (2000); 18 = New Zealand (20); Giddens et al. (1997).

significant nature of the relationship. The SOCRATES model, whilst requiring a minimal set of inputs for the long-term simulation of SOC thus appears to be highly accurate based on this wide-ranging dataset. The diversity in land use, soil type in the datasets lends support to model's utility to rapidly assess potential carbon stores under agricultural (cropped and grassland) and forested ecosystems.

There are a number of limitations to our simple approach that require further consideration. Total NPP, especially the portion allocated belowground, is difficult to predict and therefore we have utilized the best estimates from the literature in this simple approach. In addition, there is relatively poor information on the fate of C from exudations and their overall contribution to the total NPP in most studies. Predictions can also be improved as we include nutrient feedbacks on NPP in our simulations. Manipulation of carbon inputs within these systems (e.g. reduced tillage in agroecosystems) is also required, as these provide direct estimate of carbon sequestration suitable for developing greenhouse gas mitigation strategies.

Our analysis demonstrates that relatively simple process based models such as SOCRATES and ICBM (Andren and Katterer, 2001) that require minimal inputs can accurately predict temporal changes in soil organic carbon in terrestrial ecosystems. Wider use of these models and further validation, will also facilitate much needed interaction between scientists, policy makers, and the wider community in determining the impacts of land use change on greenhouse gas emissions and global climate change.

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