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ECOSYSTEMS

The Potential Impact of Agricultural Management and Climate Change on Soil Organic Carbon of the North Central Region of the United States

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ABSTRACT

Soil organic carbon (SOC) represents a significant pool of carbon within the biosphere. Climatic shifts in temperature and precipitation have a major influence on the decomposition and amount of SOC stored within an ecosystem. We have linked net primary production algorithms, which include the impact of enhanced atmospheric CO_2 on plant growth, to the Soil Organic Carbon Resources And Transformations in EcoSystems (SOCRATES) model to develop a SOC map for the North Central Region of the United States between the years 1850 and 2100 in response to agricultural activity and climate conditions generated by the CSIRO Mk2 Global Circulation Model (GCM) and based on the Intergovernmental Panel for Climate Change (IPCC) IS92a emission scenario. We estimate that the current day (1990) stocks of SOC in the top 10 cm of the North Central Region to be 4692 Mt, and 8090 Mt in the top 20 cm of soil. This is 19% lower than the pre-settlement steady state value predicted by the SOCRATES model. By the year 2100, with temperature and precipitation increasing across the North Central Region by an average of 3.9°C and 8.1 cm, respectively, SOCRATES predicts SOC stores of the North Central Region to decline by 11.5 and 2% (in relation to 1990 values) for conventional and conservation tillage scenarios, respectively.

Key words: soil carbon; simulation; North Central Region; climate change; SOCRATES; MASIF.

INTRODUCTION

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 and others 1990). With CO_2 emissions from fossil fuel combustion increasing globally by over 116 million tonnes carbon per annum (Marland and others 2003), there is 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 and others 1998). The identification of high potential regions and management strategies for sequestration in soils is an important policy objective (McCarl and Schneider 2000) and there is still great uncertainty on the actual estimates of soil

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carbon stocks and how these may be affected with respect to climate change.

The amount of carbon stored in soils is determined by the balance between primary productivity of the vegetation and the decomposition of native soil organic matter and associated litter. The abiotic influences on soil organic carbon (SOC) dynamics, such as moisture, temperature, and aeration are relatively well understood. Considering SOC storage is environment dependent, the full potential of the effects of climate on carbon cycling in terrestrial ecosystems can only be fully assessed in the context of whole-system simulation models that include these processes. The Vegetation/Ecosystem Modeling and Analysis Project (VEMAP 1995) is an example of a large, multi-institutional, international effort whose goal is to evaluate the sensitivity of terrestrial ecosystem and vegetation processes to altered climate forcing and elevated atmospheric CO_2 by using a number of terrestrial ecosystem models linking soil and plant biogeochemical processes. These complex models require an expert knowledge for parameterization and operation as well as detailed environmental inputs and are not ideally designed for rapidly assessing the impact of climate change across or between different regions.

As policy makers play increasingly important roles in addressing climate change, the ability to adequately respond to national policies and a changing socioeconomic environment is critical. Ready access to applicable information on SOC changes over time in response to management and climate, therefore, may play a major role in the development of policies and the targeting of strategies to ensure economic viability in the wake of global change. Regional assessments on the impact of climate change on SOC storage provide a greater level of detail and spatial resolution than would be feasible for a continental approach while still incorporating large, diverse, and economically important regions.

Within this context, we use the Soil Organic Carbon Reserves And Transformations in EcoSystems (SOCRATES) model (Grace and Ladd 1995) linked to the Modeling Applications System Integrative Framework (MASIF; Gage and others 2001) to assess regional changes in SOC. SOCRATES is a simple processed-based simulation model, and MASIF is a generic data handling environment, to integrate spatially explicit climate, soil and ecosystem-characterization data. We use this linked system to estimate both climate and management induced changes in SOC between the years 1850 and 2100 for the North Central Region of the United States, comprising the 12 states of North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana and Ohio, an area of 1,782,520 km^2 (excluding water bodies). The North Central Region is the major producer of corn and soybeans in the United States, and produces half of the nation's wheat. Donigan and others (1994) have estimated that half of the original pre-settlement SOC in cropping fields of what is now the Corn Belt has been released as CO_2 to the atmosphere.

METHODS

We used a simulation methodology similar to that described by King and others (1997) and coupled a net primary production (NPP) model (that is, gross photosynthetic carbon fixation less plant respiration) to a SOC model to generate a pre-agricultural SOC map (0–10 cm) of the North Central Region of the United States. This map was modified to reflect current land use change patterns up to 1990. A climate change scenario, as developed by the Intergovernmental Panel for Climate Change (IPCC) for the period 1990–2100, was superimposed onto this map to generate a year 2100 map of SOC.

Model Description

SOCRATES is a processed-based terrestrial ecosystem simulation model designed to estimate changes in topsoil SOC using a minimal set of soil, climate and biological inputs. Oades (1995) demonstrated the versatility of SOCRATES in predicting change in SOC across a wide variety of ecosystems, and the accuracy of SOCRATES for simulating changes in SOC in agroecosystems has been verified in extensive model comparisons by Skjemstad and Janik (1996) and Izaurralde and others (2001). The latter found it to be superior in accuracy to both the CENTURY (Parton and Rasmussen 1994) and RothC-26.3 (Coleman and Jenkinson 1990) models (among others) for predicting long-term carbon change in arable and rangeland soils of the Canadian prairies.

The SOCRATES model is based on four major components, two soil and two litter. All plant material can be divided into decomposable and resistant components using concepts initially described by Jenkinson (1990). The decomposable plant material is readily degraded by microbes and is related to the more succulent parts of the plant. Decomposable plant material mainly consists of sugars and carbohydrate. The resistant plant

Table 1. Parameters used to Simulate Litter Production and Soil Organic Carbon Dynamics for Major Land Uses of the North Central Region of the United States

Land use	Partition coefficient				Life span (y)				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 (DPM) to resistant (RPM) plant material.*
[b] *Proportion of total roots in top 10 cm of soil.*

material is associated with the woody structure of the plant and usually consists of cellulose and lignin. The respective decomposable/resistant plant material ratios for the litter produced from representative terrestrial ecosystems are the same as those used by Jenkinson and others (1991; Table 1). The soil components consist of microbial biomass and stable organic matter or humus. The microbial fraction is further subdivided into a transient unprotected fraction, which is involved in the initial stages of crop residue decomposition, and a protected microbial fraction, which is actively involved in the decomposition of native humus and microbial metabolites (Ladd and others 1995).

The generic description of decomposition in the model produces microbial material, humus, and CO_2 in proportions that depend on the cation exchange capacity (CEC) of the soil. These proportions and the specific decay rates for each component of the model were calibrated using the ^{14}C data of Ladd and others (1995). The first order decay rates currently used in the model are $0.84\ w^{-1}$ for decomposable plant material (that is, 84% of the material will degrade in 1 week at 25°C at optimum moisture conditions), 0.07, 0.95, 0.055 and $0.0009\ w^{-1}$ for resistant plant material, unprotected and protected microbial biomass and stable organic matter, respectively. The first order decay rates are modified using multiplicative temperature and moisture factors. The effect of temperature on decomposition is based on a Q_{10} equal to 2 [equation 1] with T representing mean annual air temperature (°C):

$$\mathrm{TF} = 0.177\ \mathrm{e}^{0.069 \times T}. \tag{1}$$

With respect to precipitation we have simplified the soil water calculations considering that this more generalized version of the model is based on annual environmental conditions. In the original model (Grace and Ladd 1995), an average monthly moisture factor of 0.21 was used to describe relative soil moisture effects on the decomposition of SOC in the presence of an actively transpiring plant in rainfed temperate environments. This moisture factor increased to 0.9 during bare fallows. We have modified this relationship to account for higher rainfall and irrigated systems including revegetated and forested ecosystems. The effect of precipitation on decomposition is described in equation (2), with P representing annual precipitation (mm):

$$\mathrm{MF} = 0.059 \times P^{0.279}. \tag{2}$$

For the purposes of this study we have also replaced the original plant production model in SOCRATES (a non-linear regression equation in response to precipitation) with a modification of the Miami model of NPP (Lieth 1975) as described in King and others (1997). This modification reflects any changes in NPP ($\mathrm{g\ m^{-2}\ y^{-1}}$) in response to changes in atmospheric CO_2 concentration and is represented by the following equation.

$$\mathrm{NPP} = \min(\mathrm{NPP}_T, \mathrm{NPP}_P)\left(1 + \beta \frac{(p - p_0)}{p_0}\right), \tag{3}$$

where "min" is a function returning the minimum value from the two NPP calculations NPP_T and NPP_P, and is based on mean annual temperature T (°C) and average annual precipitation P (mm), respectively. Explicitly

$$\mathrm{NPP}_T = \frac{3{,}000}{(1 + \mathrm{e}^{1.315 - 0.0119T})}, \tag{4}$$

$$\mathrm{NPP}_P = \frac{3{,}000}{(1 - \mathrm{e}^{-000664P})}. \tag{5}$$

The Miami model was originally derived from 52 locations around the globe and although we recognize 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. This makes it an ideal complement to the generic soil carbon dynamics model within SOCRATES and the application of the coupled model across other regions of the globe.

The CO_2 response coefficient β is essentially the same as that derived by Polglase and Wang (1992), and based on leaf photosynthetic response of C_3 plants. Its direct application to an ecosystem level community has not been verified, therefore we have followed the global example of King and others (1997) in which β is reduced to 60% of the calculated value by the use of a scale translation factor. This conversion is based on experimental studies on biomass response and photosynthetic assimilation to elevated CO_2 by Cure and Acock (1986). The state variables p and p_0 represent atmospheric and reference CO_2 concentrations, respectively.

Carbon inputs for any terrestrial ecosystem can be derived by assuming dry matter contains 40% carbon and partitioning of NPP into leaf, branch, stem and roots. As we are simulating SOC dynamics in the top 10 cm, annual root production in this layer was allocated according to Jackson and others (1996) (Table 1). The carbon density of each plant component at steady state (B) is estimated using equation (6).

$$B = \text{NPP} \times p \times Y, \tag{6}$$

where NPP is annual NPP [from equation (1)], p is the partitioning coefficient for each of the plant components and Y is the average life span (in years), for the component. The annual litter carbon input (L) for each plant component is then estimated by equation (7).

$$L = \left(\frac{1}{Y}\right) \times B. \tag{7}$$

Data Processing Environment

MASIF was developed to facilitate regional-scale long-term simulations. MASIF is characterized by a scalable data management module for rapid and ready access to input and output data; a visualization module for the exploration, description, and analysis of spatial and temporal patterns; a statistical analysis module to conduct and compare model scenarios; an output animation module to produce spatio-temporal time series of model output; and the potential to use web-based interfaces to interact with the model.

MASIF has been implemented using Visual Basic, Oracle, MS Access, ArcView, MineSet and S-Plus. These products represent a class of existing upgradeable applications, which are inherently useful for the analysis of large data sets, are widely used worldwide, and include libraries that facilitate interconnections.

Model Inputs

SOCRATES only requires mean annual temperature and precipitation data and a topsoil clay (%) or CEC value. Initial SOC values can be input, however in this study, the model itself was used to generate the pre-settlement SOC values and representative pool sizes for the soil decomposition model. Considering SOCRATES is basically a two pool soil model (microbial biomass and stable organic matter), and the relative proportions of these measurable pools are well known in the literature, the potential errors associated with this initialization approach are relatively insignificant as the model itself has been calibrated and validated against actual changes in pool sizes over the long-term. This initialization approach is considerably more sensitive to land use history and management of these ecosystems, as these impact directly on the overall size of the soil carbon pool.

Each of the 1,050 counties within the North Central Region were assigned a mean annual precipitation and temperature value based on the 1972–1990 records of the National Weather Service and a clay content (%) based on the dominant soil type within the county through interrogation of the United States Department of Agriculture (USDA)/Natural Resources Conservation Service (NRCS) database (USDA 1994). Bulk density (BD) and CEC values were assigned to each county using linear relationships we developed [equations (8) and (9)] from the Food and Agriculture Organization (FAO)/United Nations Educational, Scientific and Cultural Organization (UNESCO) Soil Map of the World—Revised Legend database (excluding Histosols) as distributed by the International Soil Reference and Information Centre (Batjes 2002):

$$\text{CEC} = (\text{mmol kg}^{-1}) = \text{clay}(\%) \times 3.91 + 57.85, \tag{8}$$

$$\text{BD}(\text{g cm}^{-3}) = 1.40 - \text{clay}(\%) \times 0.003. \tag{9}$$

Each county was assigned a dominant pre-settlement vegetation type (forest or grassland) based on the potential natural vegetation dataset of Kuchler (1964). We aggregated the 1992 National Land

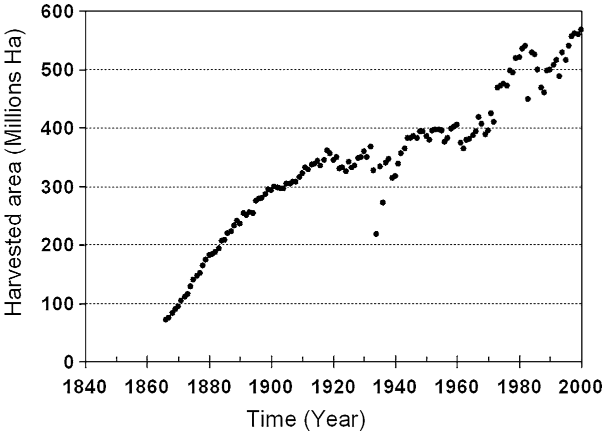

Figure 1. Historical harvested area in the North Central Region (USDA National Agricultural Statistics Service).

Cover Data (NLCD) (Vogelmann and others 2001, http://www.landcover.usgs.gov) for each county into six principal land uses (forest, grassland, shrub, agriculture, wetland, urban) and their respective areas calculated to represent post-settlement land use. 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 (that is, 25% of NPP).

Climate Change Scenarios

Counties were assigned a nominal topsoil (0–10 cm) organic carbon value of 0.5% prior to running the SOCRATES model for a minimum of 2000 years to generate steady-state SOC values based on the dominant pre-settlement vegetation for the mid 1800's. In these simulations, 3% of the initial SOC was considered to be protected microbial biomass and the remaining SOC considered to be humus, with the decomposable and resistant plant material pools initialized at 0 and 1 t C ha^{-1}, respectively.

After the pre-settlement simulations (for either forest or grassland) were completed for the 1,051 counties, the model was run for an additional 50 years. This simulated the respective changes in SOC under forest, grassland, arable (cropping) and shrub ecosystems within each county for the period 1850–1900 when the corn and wheat belts were developing across the United States. In the cropping systems we specified a minimal crop residue return rate of 15% of NPP which is typical of that and later eras (Buyanovsky and Wagner 1998).

The 1992 NLCD land use values would have significantly over-estimated the area of arable land in the North Central Region during this period (Figure 1). Therefore, for the first 25 years (1850–1875) of the simulation we reduced all of the cropping areas by 50% and added these areas to the native forest or grassland categories. For the next 25 years, we reverted to using the 1992 NLCD land use values.

This provided us with a 1900 estimate of SOC stocks for each county under each of the forest, grassland, shrub and arable land categories (with wetland and urban land areas removed from the overall county aggregate). We then ran the model from 1900 to 1945 under conventional tillage practices with minimal crop residue return (15%). By this time, the area of cropland had stabilized across the US (Ramankutty and Foley 1999). In the 1940's, management practices were modified to reduce straw removal (Lal and others 1998), so to reflect this change we simulated the gradual impact of increased crop residue retention on SOC stocks during the post-WWII period until 1990 by using a weighted average of 32% of NPP returning as residues, a value consistent with conventional practices in the Midwest (Evrendilek and Wali 2001). We chose 1990 as our baseline to be consistent with the current IPCC practice for carbon accounting.

Potential changes in topsoil organic carbon within each county in response to climate and conventional and conservation tillage (35 and 55% of NPP retained as crop residues respectively) between 1990 and 2100 were then simulated assuming no land use change relative to 1990. This version of the model does not explicitly simulate zero-tillage management, moreso the impact of retaining residues of varying quality (%N) on SOC dynamics. The respective masses of SOC in the decomposable and resistant plant material, biomass and humus pools (kg m^{-2}) in each county for 1990 had already been generated in the post-settlement model runs.

The climate change impact assessment on SOC levels is based on changes in NPP and SOC dynamics in response to predicted temperature and precipitation as provided by the CSIRO Mk2 Global Circulation Model (GCM). We compared two possible climate scenarios. Scenario A assumes no climate change over the next century with CO_2 concentration remaining constant at 354 ppm. Annual mean temperatures and precipitation for each county remained fixed at the same average values used in both the pre- and post-settlement simulations. In Scenario B, atmospheric CO_2 con-

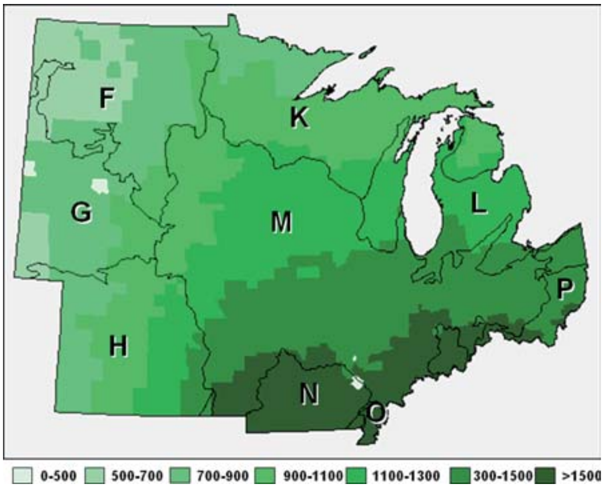

Figure 2. Predicted mean annual net primary productivity (NPP) (g m^{-2}) within Land Resource Regions of the North Central Region of the United States with no climate change as simulated by SOCRATES. (See Table 3 for description of Land Resource Regions).

centrations gradually increased to 711 ppm by the year 2100 (with an approximate 0.9%/annum increase in CO_2 after 1990). This increase was in accordance with the IPCC IS92a emission scenario. The radiative effects of stratospheric ozone and sulphate aerosols were also included. The 36 CSIRO Mk2 GCM output grids applicable to the North Central Region for 2100 were overlaid onto our county database and the relative changes in mean annual precipitation and temperature (with respect to 1990) assigned to each county. Mean annual precipitation and temperature for each of the counties were gradually increased during the 110-year simulation using an annual change scalar. By the year 2100 the mean annual precipitation was on average 8.1 cm wetter, an increase of 10% across the North Central Region relative to 1990, and an average of 3.9°C warmer.

RESULTS AND DISCUSSION

SOCRATES is a simple processed-based simulation model requiring minimal inputs to predict changes in SOC in response to litter quantity and quality, temperature and moisture. Its ability to accurately predict long-term changes in topsoil organic carbon stocks for a wide range of arable, forested, and grassland ecosystems using simplified moisture and temperature relationships to regulate decomposition rates using annual data has been demonstrated by Grace and others (in press).

In the pre- and post-settlement analyses without climate change, simulated annual NPP for the North Central Region averaged 1,220 g m^{-2} and ranged from 556 g m^{-2} in the Northern Great Plains Spring Land Resource Region of North Dakota to 1703 g m^{-2} in the East and Central Farming and Forest Land Resource Region of Missouri (Figure 2). These are in general agreement with the NPP data from cropland regions of the Mid-West US (645–1,780 g m^{-2}) (Prince and others 2001).

Our predicted estimate of pre-settlement steady state SOC in the top 10 cm of North Central Region soils is 5,807 million metric tonne (Mt) with the largest single store in Minnesota (Table 2). After 150 years of agricultural activity and land use change, these stocks declined by 19.2% to 4,692 Mt, ranging from losses of 13.5% in South Dakota to 29.7% in Illinois.

Previous estimates of SOC stocks in the North Central Region using actual survey data have been limited to the top 20 and 100 cm (Franzmeier and others 1985). To convert this data to 0–10 cm as a direct means of comparison, we used the 0–20 cm FAO/UNESCO data as summarized in Kern (1994) to develop a soil carbon distribution profile for extrapolating the data of Franzmeier and others (1985) back to 0–10 cm. Excluding organic soils (Histosols), the FAO data suggests that the 0–10 cm layer represents, on average, 58% (55.4–60.1) of the SOC in the top 20 cm. Using this assumption, our 1990 estimate of 4,692 Mt SOC (0–10 cm) using SOCRATES compares favorably with the value of 5,336 Mt for mineral soils derived by Franzmeier and others (1985) from soil surveys specific to the North Central Region. Grassland and forest soil tend to lose between 20 and 50% of their original SOC upon cultivation (Lal and others 1998), however our assessment is county rather than field based, and, for 1992, the NLCD estimates for forests and grassland still account for an average of 32% of the land area within any one county (excluding urban and wetlands).

As a further means of comparison with measured data, we then extracted the relevant spatial grids for the North Central Region from the EPA soil database developed by Kern (1994, 1995) using the USDA Soil Conservation Service national soil database and available from VEMAP (VEMAP Members 1995). Combining soil BD, organic carbon and land area data from these databases and using the same depth conversion factor of 58%, we derived a rough estimate of 8,900 Mt C for the top 10 cm of soil in the North Central Region. This value is 67% greater than the estimate reported by Franzmeier and others (1985). Using SOCRATES, our simulated 1990 estimate of 4,692 Mt C is within 14% of the value derived by Franzmeier

Table 2. The Potential Effect of Climate Change and Tillage Management[a] on Soil Organic Carbon (SOC) Stocks (0–10 cm) and Net Primary Productivity (NPP) between 1850 and 2100 for the States of the North Central Region of the United States as simulated by SOCRATES

State	SOC 1850 (Mt C)	SOC 1990 (Mt C)	SOC 2100 A CONV (Mt C)	SOC 2100 A CONS (Mt C)	SOC 2100 B CONV (Mt C)	SOC 2100 B CONS (Mt C)	NPP A[b] ($g\ m^{-2}$)	NPP B[c] ($g\ m^{-2}$)
Illinois	487.0	358.7	331.8	386.1	303.6	356.6	1,244	1,346
Iowa	457.2	321.4	299.4	354.2	272.6	326.0	1,463	1,578
Indiana	319.2	225.2	208.3	242.1	197.0	230.7	1,489	1,538
Kansas	514.8	424.6	412.1	453.0	377.2	417.1	1,174	1,285
Michigan	453.1	389.7	373.4	394.9	354.5	375.8	1,137	1,232
Minnesota	618.7	509.1	479.9	525.6	450.5	497.1	1,051	1,252
Missouri	556.7	435.4	418.8	466.1	373.9	419.4	1,530	1,675
North Dakota	524.2	449.7	427.3	460.7	396.8	430.1	701	809
Nebraska	501.9	432.0	417.6	448.5	388.9	419.3	963	1,058
Ohio	370.8	281.8	264.2	295.4	249.6	280.4	1,423	1,466
South Dakota	536.2	463.8	445.6	477.8	415.4	447.2	903	993
Wisconsin	466.9	400.3	383.8	411.1	370.4	399.3	1,124	1,343
Total NCR	5,806.7	4,691.8	4,462.3	4,915.4	4,150.4	4,599.0	1,183	1,298

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[a] *A = No climate change with CO_2 constant at 354 ppm and mean annual temperature and precipitation remaining at pre-1990 conditions; B = Climate change with CO_2 increasing to 711 ppm by 2100 and mean annual temperature and precipitation conditions increasing as per the IPCC IS92a emission scenario (including sulphate aerosols) generated by the CSIRO Mk2 GCM (5 October 1998); CONV = Conventional tillage with 35% of NPP returned to the soil as crop residues; CONS = Conservation tillage with 55% of NPP returned to the soil as crop residues.*

[b] *Mean annual NPP for pre- and post-settlement simulations without climate change (Scenario A).*

[c] *Mean annual NPP for 2100 in response to climate change (Scenario B).*

and others (1985). The relatively large discrepancy between SOC value derived using the VEMAP dataset and the estimates of both Franzmeier and ourselves may be due to resolution of the soil survey data used in each of the these studies. The VEMAP database utilized soils information from the National Soil Geographic Database (NATSGO) (USDA 1982) at 1:7,500,000 resolution. Franzmeier and others (1985) used a 1:2,500,000 soil map of the North Central Region, whereas our simulations were based on STATSGO data at 1:250,000 resolution. We therefore used our estimates as the basis for projections to avoid any bias in comparison of projected and historical estimates.

We estimate that the 496 counties within the Corn Belt (Land Resource Region M), contain 35.3% of the 1990 SOC store of the North Central Region (Table 3), with the SOC in the topsoil of the counties within the Corn Belt declining by an average of 26.9% since agricultural activities commenced in the mid 1800's. The largest predicted stores of SOC (0–10 cm) within the Corn Belt in 1990 were in Iowa (359 Mt) and Illinois (303 Mt), with the largest single store in the Northern Great Plains Spring Wheat Region of North Dakota (443 Mt). When combined with 332 Mt in the Central Great Plains Winter Wheat and Range, these four (out of a possible 32) State × Land Resource Region areas contain over 30% of all the topsoil organic carbon in the North Central Region.

Under Scenario A, with no change in climate, NPP, or CO_2 concentration relative to 1990 and with 35% of the NPP in agricultural (cropping) systems returned to the soil as litter throughout the twenty-first century to mimic conventional tillage, SOCRATES simulated a further 4.9% decline in SOC stocks in the North Central Region, between 1990 and 2100, equivalent to 230 Mt C in the top 10 cm. Half of this loss is from Corn Belt soils. If additional crop residues had been retained, as would normally be the case with conservation tillage, the model simulated an increase in SOC stocks of 4.8% relative to 1990 levels. The largest gain was in the Corn Belt with 135 Mt C.

Under Scenario B, the CSIRO Mk2 GCM predicts that by the year 2100, annual precipitation and temperature for the North Central Region will have increased by 8.1 cm and 3.9°C, respectively (relative to 1990 levels). Predicted changes in precipitation across the North Central Region range from an increase of 23 cm in southern Missouri to a small decrease in Indiana and Ohio. Projected temperature changes across the North Central Region range from +3.4 to +4.5°C. With climate change, the average NPP for the region simulated by SOCRATES for the North Central Region had increased by 9.3% (to 1,334 $g\ m^{-2}$) relative to the no climate change scenario, with the largest overall increase being 200 $g\ m^{-2}$ for the state of Wisconsin, followed closely by Minnesota and North Dakota (Figure 3).

Table 3. The Potential Effect of Climate Change and Tillage Management[a] on Soil Organic Carbon (SOC) Stocks (0–10 cm) and Net Primary Production (NPP) between 1850 and 2100 for the Land Resource Regions of the North Central Region of the United States as simulated by SOCRATES

Land Resource Region[b]	SOC 1850 (Mt C)	SOC 1990 (Mt C)	SOC 2100 A CONV (Mt C)	SOC 2100 A CONS (Mt C)	SOC 2100 B CONV (Mt C)	SOC 2100 B CONS (Mt C)	NPP A[c] (g m^{-2})	NPP B[d] (g m^{-2})
F	816.8	692.3	656.7	712.4	609.2	664.6	778	887
G	402.4	383.9	379.4	387.9	357.5	366.0	806	871
H	587.6	493.0	476.9	519.3	440.9	482.7	1,027	1,122
J	4.5	4.1	4.1	4.3	3.7	3.9	1,499	1,653
K	763.0	696.1	676.8	701.2	649.7	675.9	1,026	1,282
L	448.1	339.8	314.4	354.2	297.3	337.1	1,245	1,298
M	2266.1	1656.5	1541.9	1791.7	1416.7	1662.1	1,339	1,444
N	426.3	359.2	349.2	372.9	317.3	340.2	1,559	1,670
O	25.7	15.6	14.6	18.1	12.7	16.0	1,681	1,866
P	66.2	51.2	48.2	53.4	45.3	50.5	1,392	1,530
Total	5806.7	4691.8	4462.3	4915.4	4150.4	4599.0	1,235	1,362

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[a] *A = No climate change with CO_2 constant at 354 ppm and mean annual temperature and precipitation remaining at pre-1990 conditions; B = Climate change with CO_2 increasing to 711 ppm by 2100 and mean annual temperature and precipitation conditions increasing as per the IPCC IS92a emission scenario (including sulphate aerosols) generated by the CSIRO Mk2 GCM (5 October 1998); CONV = Conventional tillage with 35% of NPP returned to the soil as crop residues; CONS = Conservation tillage with 55% of NPP returned to the soil as crop residues.*

[b] *F, Northern great plains spring; G, Western great plains and irrigated; H, Central great plains winter wheat and range; J, Southwestern prairies cotton and forage; K, Northern lake states forest and forage; L, Lake states fruit, truck and dairy region; M, Central feed grains and livestock; N, East and central farming and forest; O, Mississippi delta cotton and feed grains; P, South Atlantic and Gulf slope cash crops, forest, and livestock.*

[c] *Mean annual NPP for pre- and post-settlement simulations without climate change (Scenario A).*

[d] *Mean annual NPP for 2100 in response to climate change (Scenario B).*

In Scenario B, SOCRATES simulated a 11.5% decline in SOC stocks between 1990 and 2100 under conventional tillage in the North Central Region, equivalent to 542 Mt C in the top 10 cm, the largest losses being from the Corn Belt with a 14.5% decline in SOC. Under conservation tillage (simulated through increased crop residue retention), the loss in SOC was restricted to only 2% of the 1990 level, with the Corn Belt the only Land Resource Region not losing SOC relative to 1990 levels. In all, implementation of conservation tillage across the North Central Region would increase SOC stores by 450 Mt relative to conventional tillage over the same time period (Figure 4).

Spatial patterns of SOC concentration across the North Central Region for the pre- and post-settlement (1990) conditions, as well as the four climate × management scenarios, are presented in Figure 5. SOCRATES simulated an average topsoil (0–10 cm) organic carbon concentration of 3.37 kg m^{-2} across the North Central Region under forest and grassland, prior to settlement. After 140 years of agriculture, the average SOC concentration value was 2.64 kg m^{-2} across the counties of the North Central Region, a decline of nearly 22%. This visualization clearly identifies some areas of concern if conventional tillage remains in widespread practice under a changing climate (that is, Figure 5E). Although it is not possible to define the critical thresholds in SOC concentration below which crop production will be compromised, SOC concentrations in the western extent of the Corn Belt and across the Central Great Plains Winter

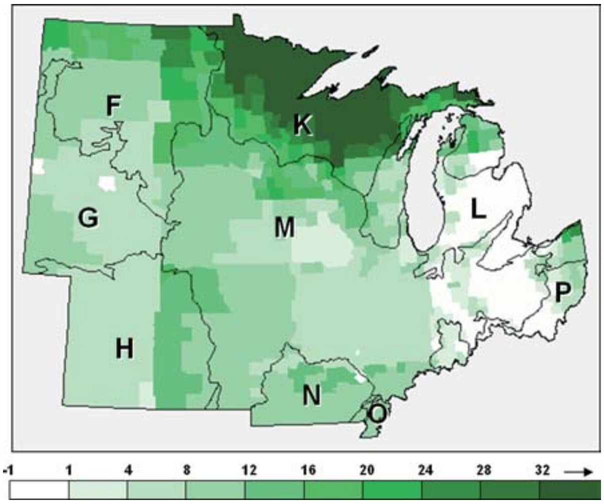

Figure 3. Predicted change (%) in net primary productivity (NPP) across the North Central Region of the United States between 1990 and 2100, in response to an average increase in mean annual precipitation and temperature of 8.1 cm and 3.9°C, respectively, as simulated by SOCRATES. (See Table 3 for description of Land Resource Regions).

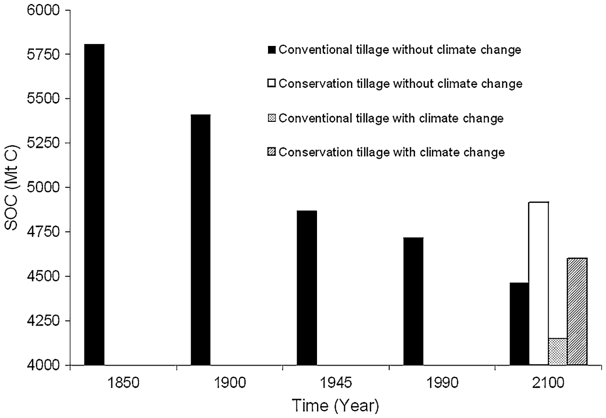

Figure 4. Soil organic carbon stocks (Mt) (0–10 cm) of the North Central Region from 1850 to 2100 as simulated by SOCRATES in response to climate change and tillage practices.

Wheat and Range Land Resource Region, specifically in the states of Kansas and Nebraska, as well as through the Corn Belt of central Illinois, indicate these soils are particularly at risk.

Conclusions

Climate change effects on the terrestrial carbon cycle are principally driven by the response of vegetation to these changes. Decomposition of organic material is also influenced by the same temperature and precipitation inputs that drive vegetative growth. We have attempted to predict the impact of these environmental variables on the cycling of SOC in terrestrial ecosystems of the North Central Region through the twenty-first century. Our estimates are based on combining a broad classification of the soils of the North Central Region with summary soil survey and climate data at the county level. The size of the North Central Region and the large amount of variability in soil carbon characteristically found across a landscape also places limits on the utility of the current store of soil survey information. Our model indicates that the North Central Region has lost 19.2% of its SOC since inception of agricultural practices in the mid-1800's. The fact that our simulated present-day value for SOC for the top 10 cm (4,692 Mt) is within 14% of that derived by Franzmeier and others (1985), who used local soil survey records, leads us to believe our estimate is plausible. This result also leads us to believe that SOCRATES is a suitable process based model for assessing the impact of future climate on NPP and relative changes in SOC stocks in terrestrial systems using some general assumptions on land use and SOC distribution.

We have assumed no change in current land use at a county level and compared conventional and conservation tillage. In our no climate change scenario, with the widespread use of conservation tillage, the top soils of the North Central Region will sequester 224 Mt C over the next century, an increase of 4.8% over present-day stocks. We predict that SOC stocks will be a source of CO_2 to the atmosphere over the next 100 years if there is pronounced climate change. In our worse case scenario, based on an overall warming of the region of about 4°C and conventional tillage, the top soils (0–10 cm) of the North Central Region will emit 542 Mt C, a loss of 11.2% over the next 100 years. Over half of this loss (311 Mt C) is directly attributed to warming.

There are a number of limitations to our approach that should be taken into account for future studies. Total NPP is difficult to measure and we have used a simple empirical estimation based on temperature or precipitation. In addition, there is relatively poor information on the fate of carbon from exudations and their overall contribution to the total NPP in most studies. Predictions can also be improved by including nutrient feedbacks on NPP into simulations.

We have assumed that current vegetation type did not change in response to climate change nor do we have a meaningful methodology for projecting future land use changes, which could have as great an impact as climate and CO_2 changes. For increased accuracy, successional change algorithms should also be included into models as species composition has a major bearing on nutrient turnover. Spatial variability in soil properties and rainfall across the landscape also has to be considered, however most of the listed limitations would require a more complex model and defeat the purpose of using simple predictive approaches for wider policy level decisions.

Simulation models of soil carbon cycling are improving as modelers work more closely with experimental scientists to develop models that use measurable fractions or surrogates based on pedotransfer functions. This paper has demonstrated that relatively simple processed-based models such as SOCRATES and the Introductory Carbon Balance Model (ICBM) (Andren and Katterer 2001), which do not require detailed analyses or inputs to perform accurate simulations, provide a promising avenue for researchers and policy makers to predict the impacts of climate change on the cycling of carbon in terrestrial ecosystems.

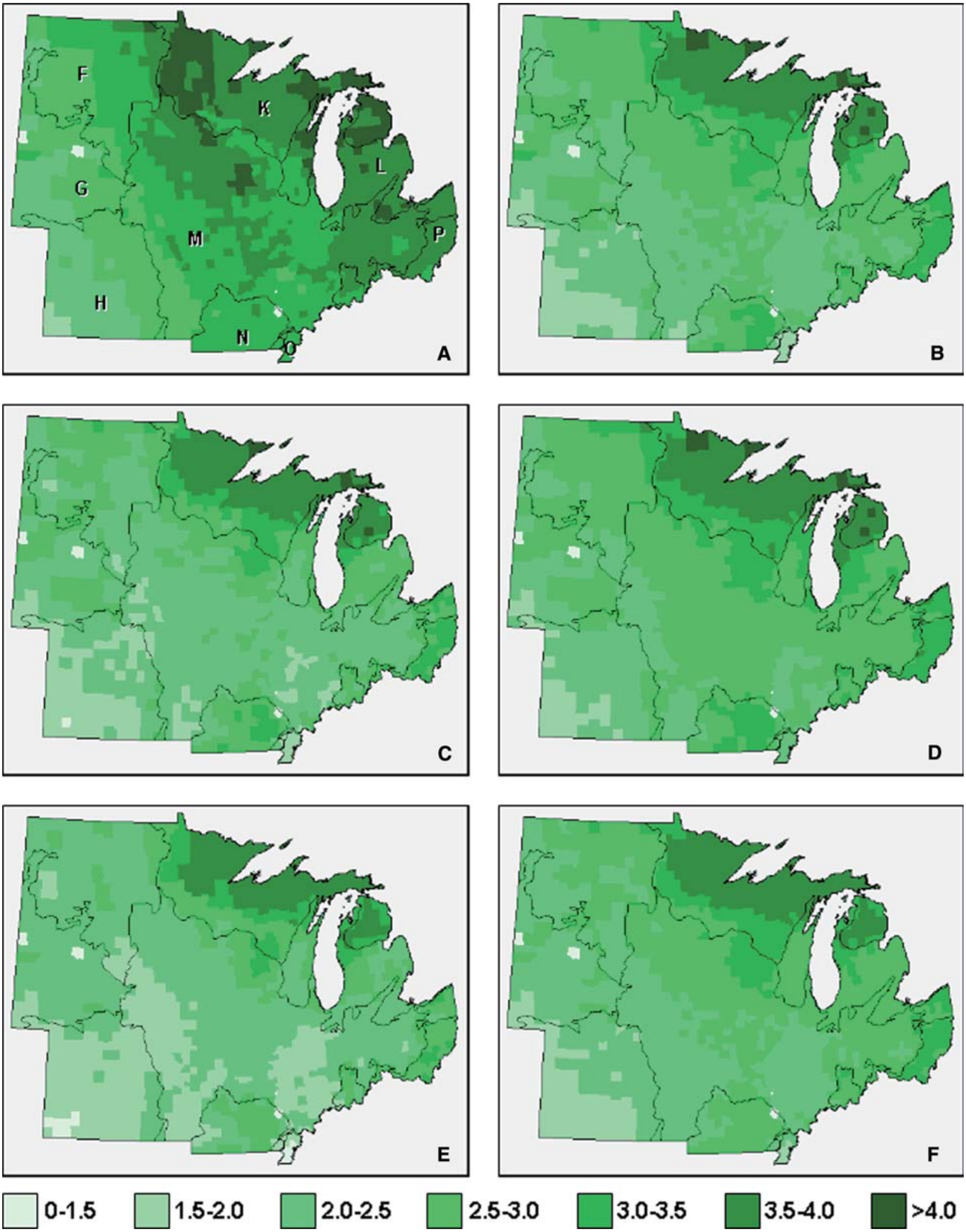

Figure 5. Soil organic carbon concentrations (kg m^{-2}) (0–10 cm) within Land Resource Regions of the North Central Region of the United States. Presettlement (**A**), current (**B**), conventional tillage under no climate change (**C**), conservation tillage under no climate change (**D**), conventional tillage under climate change (**E**), conservation tillage under climate change (**F**), (See Table 3 for description of Land Resource Regions).

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