Assessing the impact of changes in climate and CO_2 on potential carbon sequestration in agricultural soils

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[1] Changes in soil management can potentially increase the accumulation of soil organic carbon (SOC), thereby sequestering CO_2 from the atmosphere. However, the amount of carbon sequestered in soils can be augmented or lessened due to changes in climate and atmospheric CO_2 concentration. The purpose of this paper is to study the influence of climate and CO_2 feedbacks on soil carbon sequestration using a terrestrial carbon cycle model. Model simulations consist of observed adoption rates of no-tillage practices on croplands in the U.S. and Canada between 1981–2000. Model results indicate potential sequestration rates between 0.4–0.6 MgC/ha/yr in the Midwestern U.S. with decreasing rates towards the western, dryer regions of the U.S. It is estimated here that changes in climate and CO_2 between 1981–2000 could be responsible for an additional soil carbon sequestration of 42 Tg. This is 5% of the soil carbon estimated to be potentially sequestered as the result of conversion to no-tillage in the U.S. and Canada.
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1. Introduction

[2] Soil carbon sequestration has been shown to be an important part of a portfolio of strategies to stabilize atmospheric CO_2 at less than double the preindustrial concentration [*Pacala and Socolow*, 2004], and one that can be implemented at relatively low costs [*McCarl and Schneider*, 2001]. However, the difference between natural sink options, such as soil carbon sequestration, and other options, consisting of actions in energy conservation, is that there exist climate and atmospheric CO_2 feedbacks that can alter the amount of carbon sequestered under the natural sink options. Changes in climate, specifically temperature, have been shown to have a direct impact on soil C stocks [*Melillo et al.*, 2002], with increasing temperature causing increased soil C efflux and the efflux distributed over time differently for fast, intermediate, and slow turnover soil pools [*Knorr et al.*, 2005]. *Thornley and Cannell* [2001] hypothesize that a climate warming will cause a loss of soil carbon in the short-term, but that soil carbon losses in the long-term will be offset by increases in carbon input to the soil and by physical-chemical reactions that stabilize soil carbon.

[3] The purpose of this modeling analysis is to estimate how carbon sequestration is augmented or lessened as a result of changes in climate, specifically changes in temperature, precipitation, and the atmospheric CO_2 concentration. Our analysis focuses on carbon sequestered in soil as a result of a change from conventional plow tillage (CT) to no-till (NT). No-till is among the most promising cropland management strategies for accumulating soil carbon [*Paustian et al.*, 2000; *Follett*, 2001; *West and Post*, 2002]. No-till, among other conservation tillage practices, leaves at least 30% ground coverage by crop residue and reduces soil disturbance and soil carbon decomposition by not plowing or inverting the soil surface. Our analysis considers the current and maximum adoption of NT in North America (i.e., United States and Canada) and the resulting uptake of CO_2 from 1981–2000 using a terrestrial ecosystem component of the Integrated Science Assessment Model (ISAM-2) [*Jain and Yang*, 2005].

[4] In particular, we will answer the following questions: How will changes in climate and atmospheric CO_2 affect the sequestration of soil carbon in North America? Will there be a positive, negative, or insignificant interaction between soil carbon sequestration and climate change? In which climate region(s) will the interaction be most pronounced? Answers to these questions will help estimate the net impact of soil carbon sequestration efforts on carbon fluxes in North America, and will help separate changes in carbon stocks due to changes in management from those occurring naturally or from changes in climate and CO_2.

2. Model Description

[5] The terrestrial component of ISAM-2 simulates carbon fluxes within the terrestrial biosphere at a $0.5° \times 0.5°$ spatial resolution [*Jain and Yang*, 2005]. Each grid cell is occupied by at least one of the 12 natural land-cover classifications based on vegetation datasets from *Loveland and Belward* [1997] and *Haxeltine and Prentice* [1996]. Each grid cell is also assigned one of 105 soil types from the FAO-UNESCO Soil Map of the World [*Zobler*, 1999] for determining soil properties used in computing the initial soil carbon steady state case in 1765.

[6] The carbon dynamics of vegetation pools are based on *Jain and Yang* [2005], whereas dynamics of the litter and soil pools are consistent with those in the Rothamsted soil carbon model (Roth-C) [*Coleman and Jenkinson*, 1999]. The ISAM-2 simulates plant photosynthesis, respiration, and the distribution of carbon in plant material. The model also includes a CO_2 fertilization effect on biomass and the effects of temperature on photosynthesis and respiration.

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Decomposition rates are determined by temperature, soil moisture, and a plant protection factor. Soil moisture depends on evapotranspiration, thereby resulting in a close link between the plant and soil model components in ISAM-2. The structure, parameterization, and performance of the ISAM-2 have been previously discussed [*Jain and Yang*, 2005].

[7] To estimate carbon sequestration in soils, following a change in cropland management from CT to NT, we use empirically-based sequestration estimates that represent the mean annual change in soil carbon over the expected duration of active sequestration [*West et al.*, 2004; T. O. West and J. Six, Considering the influence of sequestration duration and carbon saturation on estimates of soil carbon capacity, submitted to *Soil Science*, 2005]. These empirical relationships, or carbon management response (CMR) curves, have been developed for changes from CT to NT over five climate regions: Cold Temperate Dry (CTD), Cold Temperate Moist (CTM), Warm Temperate Dry (WTD), Warm Temperate Moist (WTM), and the tropics (TROP). These climate regions are consistent with those used in the IPCC guidelines for carbon accounting [*Intergovernmental Panel on Climate Change* (*IPCC*), 2003; *Eve et al.*, 2001], except that the values for tropical dry (TD), tropical moist (TM), and tropical wet (TW) in this analysis were combined in one TROP category due to a lack of sufficient data for individual TD, TM, and TW regimes. Figure A1 in the auxiliary material[1] illustrates these climate regions in North America. The CMR curves represent the percent change in soil carbon following a change in tillage. Starting in year 1981, this percent change is applied in the model such that the difference between the CT and NT simulations results in a percent change in soil carbon equal to that represented by the CMR curves (Figure 1).

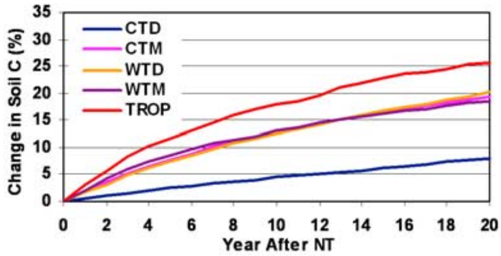

Figure 1. Mean percent change in soil C estimated by ISAM-2 across five climate regions in North America following a change from conventional tillage (CT) to no-till (NT). The five climate regions are CTD: Cold Temperate Dry; CTM: Cold Temperate Moist; WTD: Warm Temperate Dry; WTM: Warm Temperate Moist; and TROP: Cold and Warm Tropics.

3. Model Simulations Performed

[8] The ISAM-2 was initialized with an atmospheric CO_2 concentration of 278 ppmv, representative of approximate conditions in 1765, to allow vegetation and soil carbon pools to reach an initial steady state. Figure A2 illustrates the model-estimated steady state soil carbon in North America. Historical changes in soil carbon stocks in North America were simulated between 1765–1980 based on observed temperature and precipitation changes (T. D. Mitchell et al., A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: The observed record (1901–2000) and 16 scenarios (2001–2100), submitted to *Journal of Climate*, 2003), changes in the atmospheric CO_2 concentration during this same time period [*Keeling and Whorf*, 2000], and changes in land cover for croplands [*Jain and Yang*, 2005]. Changes in no-till management were simulated from 1981–2000, with and without changes in climate and CO_2, as described below. Changes in cropland area continue to be simulated during this time period in all experiments, thereby canceling the effect of land-use change when comparing changes in soil carbon with and without changes in CO_2 and climate. Historical changes in cropland area for the period 1765–1992 are based on *Ramankutty and Foley* [1998, 1999]. For the period between 1992 and 2000, we linearly extrapolated cropland area within each grid cell based on land-use trends in the previous decade.

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023922.

3.1. Adoption of No-Till Crop Management With Changes in Climate and CO_2 (NTWC)

[9] In this modeling experiment, NT is simulated in ISAM-2 using CMR curves for the period 1981–2000. Changes in climate, land use and CO_2 are from the same sources as those used prior to 1981. Adoption of NT is simulated for all combinations of climate regions and soil types. A weighted average of the changes in soil carbon within each climate region is calculated and averaged over a 20-yr period.

[10] The weighted average rate of potential sequestration for each climate region is later multiplied by the area under NT to estimate sequestration rates in North American climate regions over the period 1981–2000. These sequestration rates represent the baseline case with varying climate and CO_2 (defined as BWC). In 2000, NT had been adopted in the U.S. and Canada on about 18% and 30% of cropland, respectively [*Conservation Technology Information Center*, 2000; *Statistics Canada*, 2001]. The percent adoption is highly variable over space and time, and we apply annual adoption rates of NT based on soil tillage survey data at the U.S. State and Canadian Province levels. Sequestration rates estimated in the NTWC experiment are also applied over all or 100% of North America cropland area to provide an estimate of maximum sequestration potential with changes in climate and CO_2 (defined as MWC). We note here that full adoption may not be technically possible or economically feasible, and that an analysis by *McCarl and Schneider* [2001] indicate the maximum potential adoption of NT in the U.S. at about 80%.

3.2. Adoption of No-Till Crop Management Without Changes in Climate and CO_2 (NTWOC)

[11] In this experiment, NT is again simulated, but climate and CO_2 are held constant at 1980 levels. Subtracting these estimates from those in the NTWC experiment provides an estimate of the impact of recent changes in climate and CO_2 on current and future potential soil carbon sequestration. As with the NTWC experiment, the sequestration rates estimated here on an

Table 1. Total Cropland Area, Cropland in No-Till (NT), and Sequestration Rates for NT With and Without Changes in Climate and CO_2[a]

Climate Regions[b]	Cropland Area, Mha	NT Area, Mha	Modeled Experiments,[c] MgC ha^{-1} yr^{-1} NTWC	NTWOC	Sequestration Cases,[d] TgC yr^{-1} BWC	BWOC	MWC	MWOC
CTD	79.80	21.34	0.694	0.675	14.80	14.40	55.38	53.85
CTM	68.11	18.21	0.569	0.548	10.36	9.98	38.75	37.35
WTD	31.09	8.31	0.595	0.570	4.94	4.74	18.50	17.71
WTM	79.67	21.31	0.445	0.404	9.48	8.62	35.45	33.38
TROP	19.31	5.16	0.741	0.689	3.82	3.56	14.31	13.31
Total	279.88	74.34	0.584	0.556	43.41	41.33	163.45	156.79

[a]The total cropland and NT area is given for the year 2000, while sequestration rates are averaged for the period 1981–2000.
[b]CTD: Cold Temperate Dry; CTM: Cold Temperate Moist; WTD: Warm Temperate Dry; WTM: Warm Temperate Moist; TROP: Cold and Warm Tropics.
[c]NTWC: No-till with changes in climate and CO_2; NTWOC: No-till without changes in climate and CO_2.
[d]BWC: Base case with varying climate and CO_2; BWOC: Base case with constant climate and CO_2 at their 1980 levels; MWC: Maximum NT case with varying climate and CO_2; MWOC: Maximum NT case with constant climate and CO_2 at their 1980 levels.

annual and per area basis are then multiplied by the area estimated to be in NT in 2000 (defined as BWOC) and the total or 100% of North America cropland area in 2000 (defined as MWOC).

4. Results and Discussion

[12] Sequestration rates simulated by ISAM-2, not including the influence of changes in climate and CO_2, for North America averaged over the period 1981–2000 range from 0.4–0.7 Mg C ha^{-1} yr^{-1} (Table 1). These rates are on the high end of those provided by the *IPCC* [2000] in different climate regions. *IPCC* [2000] estimated relatively higher sequestration rates for temperate and tropical wet regions and boreal regions (~0.2–0.8 Mg C ha^{-1} yr^{-1}) compared to rates for temperate and tropical dry regions (~0.1–0.3 Mg C ha^{-1} yr^{-1}). Similarly, estimates of the percentage change in soil carbon by ISAM-2 for different climate regions are relatively low in CTD regions and greater in TROP regions (Figure 1).

[13] However, the potential amount of carbon sequestered in the CTD region is relatively high (Figure 2 and Table 1) due in part to the higher initial soil carbon content (Figure A2). High sequestration potentials were also estimated for the WTD and TD regions in Texas (Figure 2). This is due to a combination of relatively higher sequestration rates for TROP regimes (Figure 1), high initial soil carbon content in central Texas (Figure A2), and feedback effects of climate and CO_2 on soil carbon (Figure 3).

[14] An analysis by *Franzluebbers and Steiner* [2002] on potential carbon storage in agricultural lands concludes that the greatest potential may be found in climate regions with a mean annual precipitation-to-potential evapotranspiration (PET) ratio of 1.1 to 1.4, with optimal sequestration around 1.27 (Figure A3). We similarly estimate decreased sequestration potential west of 95° longitude (Figure 2), which coincides with the precipitation to PET ratio threshold of about 1.1 (Figure A3). However, contrary to *Franzluebbers and Steiner* [2002], ISAM-2 simulations indicate high potential sequestration in "more extreme environments", such as the colder region in western Canada, and the warmer, dryer region in Texas as discussed above (Figure 2).

[15] The average response of sequestration rates to historical changes in climate and CO_2 is positive (compare NTWC and NTWOC categories in Table 1). This positive effect is in agreement with results from a 4-yr experiment in Alabama [*Prior et al.*, 2005] that measured a 44% increase in soil carbon under conservation management (no-till with winter cover crops) with elevated CO_2 compared to ambient CO_2. Elevated CO_2 with conventional management (winter fallow and spring tillage) did not produce a statistically significant increase in soil carbon.

[16] The spatial distribution of the difference between sequestration rates with and without changes in climate and CO_2 is highly variable (Figure 3). This is expected due to the number of variables modeled and the interactions between these variables. Areas within the WTD, WTM, and TROP regions, particularly in the eastern U.S. and tropical regions (Florida and Texas), show increased soil carbon sequestration with recent changes in climate and CO_2. Sequestration potentials in the northern U.S. and in central and western Canada appear less affected by changes in climate and CO_2 than areas in the southern U.S. (Figure 3).

5. Conclusions

[17] Our model results indicate that NT practices with changes in climate and CO_2 between 1981–2000 in the U.S. and Canada have sequestered about 868 Tg C (or 43.4 Tg C/yr) in soils (Table 1). Without changes in climate and CO_2, NT practices would have sequestered about 826 Tg C (or 41.3 Tg C/yr) (Table 1). These model

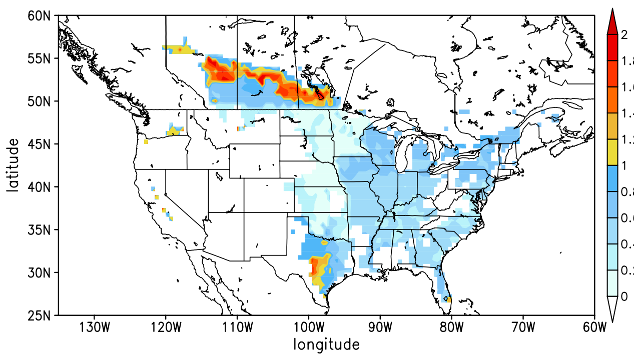

Figure 2. Soil carbon sequestration potential estimated by ISAM-2, with changes in climate and CO_2, following a change from conventional tillage to no-till and averaged over the period 1981–2000. Units of sequestration (MgC/ha/yr) are for cropland areas within grid cells that adopted NT during this time period.

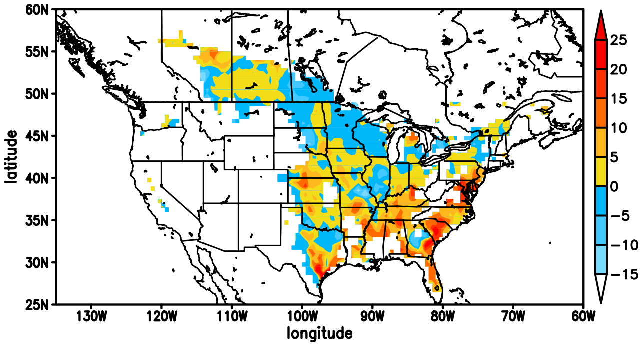

Figure 3. Percent difference between adopted NT with changes in climate and CO_2 (NTWC experiment) and adopted NT with no changes in climate and CO_2 (NTWOC experiment). Positive and negative values indicate an increase or decrease, respectively, in soil C sequestration potential due to changes in climate and CO_2.

estimates indicate that changes in climate and CO_2 were responsible for about 42 Tg or 5% of the soil C sequestered under NT. If we run simulations with and without changes in land use only, results indicate that changes in land use alone would cause an additional 3% (27 Tg C/yr) accumulation of soil carbon.

[18] Within the U.S., higher sequestration potentials are estimated for the temperate moist regions (Figure 2), which coincide with a precipitation-PET ratio of greater than 1.0 (Figure A3). Exceptions to this pattern include the tropical dry and tropical moist regions of south-central Texas and southern Florida, respectively, which show relatively high rates of potential sequestration. Relatively high rates of carbon sequestration are also indicated in the CTD region of Canada.

[19] The net impact of climate and CO_2 change during 1981–2000 on the potential to sequester soil carbon is relatively small in colder regions (CTD and CTM), compared to the larger positive impact estimated for warm (WTD and WTM) and tropical regions. Reasons for varied responses from north to south and east to west include varied geographical pattern of soil moisture changes, increased soil temperatures in colder regions, and temperature dependence of CO_2 fertilization resulting in a lower response of NPP and therefore litter inputs in colder climates than in warmer ones. In some regions, these three effects work together in a positive interaction, while in others they offset each other.

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Auxiliary Material for Paper 2005GL023922

Assessing the Impact of Changes in Climate and CO_2 on Potential Carbon Sequestration in Agricultural Soils

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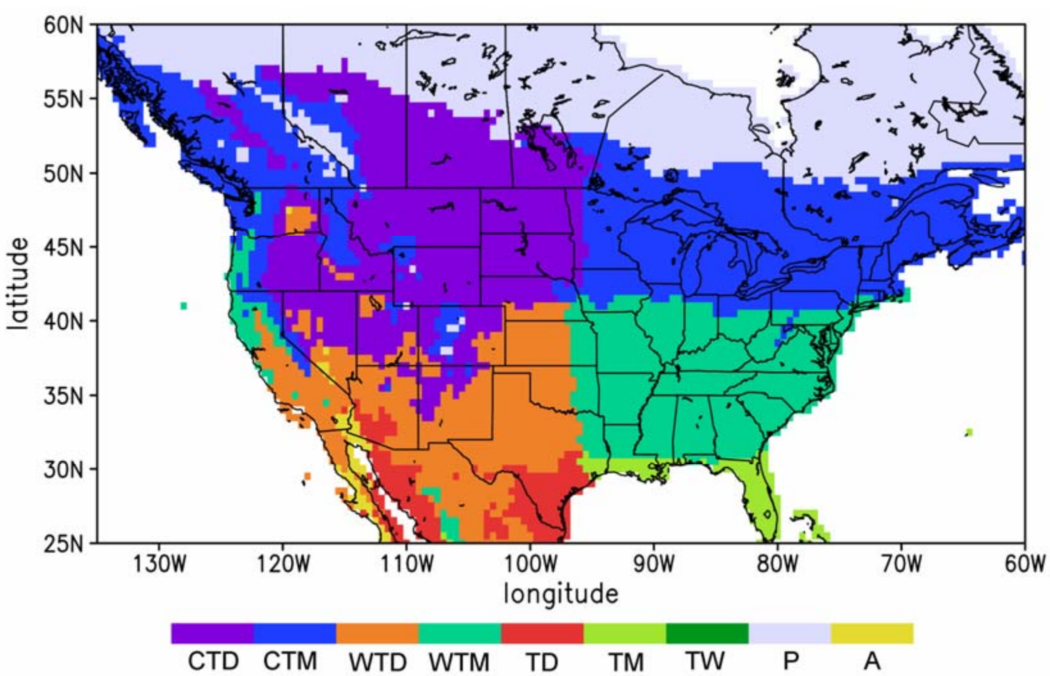
Introduction

This supplement includes three figures to show the climate regions distribution(Figure A1), Initial soil carbon content in 1765 (Figure A2) and Ratio of mean annual precipitation to mean annual potential evapotranspiration(Figure A3). The aim of these figures is to support the explanation given in the paper.

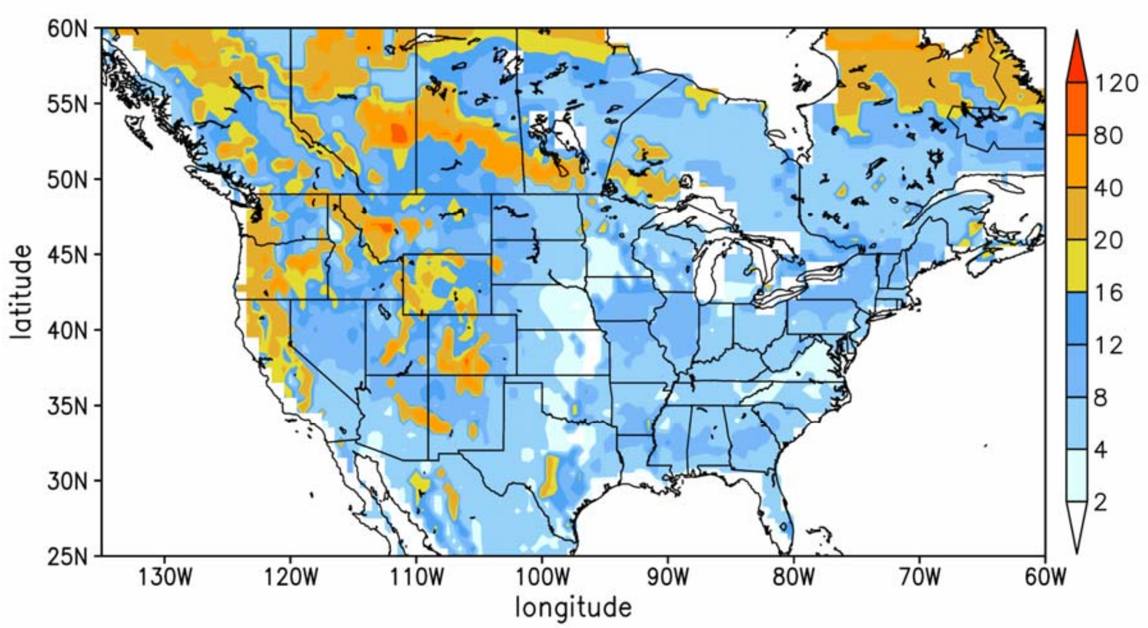
1. 2005GL023922-FigureA1.eps

Climate Regions delineated according to Eve et al. (2001) and IPCC (2003).Climate classifications are cold temperate dry (CTD), cold temperate moist (CTM), warm temperate dry (WTD), warm temperate moist (WTM), tropical dry (TD), tropical moist (TM), tropical wet (TW), Polar (P), and Arid (A).



2 2005GL023922-FigureA2.eps

Initial soil carbon content in 1765 (kg/m2 per 30cm depth) used in ISAM-2 simulations.



3. 2005GL023922-FigureA3.eps

Ratio of mean annual precipitation to mean annual potential evapotranspiration.