Estimating Soil C Sequestration Potential in U.S. Agricultural Soils Using the IPCC Approach

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Abstract

Field studies across the U.S. have been used to estimate soil C stock changes that result from changes in agricultural management. Data from these studies are not easily extrapolated to reflect changes at a national scale because soils and climate vary locally and regionally. These studies are also limited to addressing existing changes in agricultural management and cannot be easily or reliably extended to estimate soil C changes from agricultural management changes that were not a part of the study. The Intergovernmental Panel on Climate Change (IPCC) developed comprehensive methods for inventorying greenhouse gas emissions that cover a full range of anthropogenic influences on sources and sinks of greenhouse gases. We applied the IPCC spreadsheet-based method combined with land use and cropping information from the National Resources Inventory (NRI), climate data and tillage practices to estimate soil C storage potential in U.S. agricultural mineral soils. We analyzed potential soil C accumulations from increased adoption of no-till, decreased bare fallow operations, conversion of highly erodible land to set-aside land, and increased use of cover crops in annual cropping systems. The data presented represent potentials that do not consider the economic or agronomic feasibility of proposed agricultural production changes, but provide an indication of the biophysical potential of soil C sequestration that may be used for policy prescriptions. Adoption of no-till for all agricultural production has the potential of increasing soil C sequestration from 20.2 MMTC yr^{-1} to 50.5 MMTC yr^{-1}. Elimination of fallow operations and crop production on highly erodible land provide potential soil C sequestration increases from 20.2 MMTC yr^{-1} to 23.2 MMTC yr^{-1} and 31.1 MMTC yr^{-1} respectively. The soil C sequestration potential from including a winter cover crop on annual cropping systems is 43.1 MMTC yr^{-1}.

Introduction

Cultivated U.S. agricultural soils have been estimated to contain 20-40% less soil carbon (C) than soils that were never cultivated (Davidson and Ackerman, 1993; Mann, 1985). The loss of soil C resulting from conversion of undisturbed land to annual cropping may be reversed through certain land use and management practices (Lal et al., 1998). Allmaras et al. (2000) determined that U.S. cropland soils shifted from a C source to a C sink during the last fifteen years, primarily due to changes in tillage practices away from moldboard plow. Eve et al. (2001) estimated that soil C in U.S. agricultural soils increased by over 8 million metric tons per year (MMT yr^{-1}) between 1982 and 1992 due to changes in land use and agricultural management practices.

Many facets of agricultural land management and land use change have been examined for their potential to increase soil C stocks (Bruce et al., 1999; Lal et al., 1998; Lal et al. 1999; Paustian et al., 1997a; Paustian et al., 1997b). While these earlier analyses have been useful in providing a first-order estimate of sequestration potential, they have been based on highly aggregated data. Often a single nominal value of C change rates (i.e. Mg ha yr^{-1}) or % C stock increase, multiplied by an aggregate land area for the U.S., for a given practice was applied. Thus, these estimates do not incorporate the interaction of climate, soil and management, which varies spatially across the cropland area of the U.S., on C sequestration potential.

Objective

Our objective was to estimate potential soil C changes on U.S. agricultural soils using detailed data on soils, climate, tillage, and crop rotations, and their geographic distribution. Soil C sequestration potentials were derived using a modified version of the C emission/sink calculation in the Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1997a, b, c) and assumptions about increased adoption of no-till, set-aside land, inclusion of winter cover crops, and reduced bare summer fallow. These land use and land management activities are among the practices that provide the greatest increase in soil C on agricultural soils (Cole et al., 1993; Lal et al., 1998, 1999; Bruce et al., 1999; Paustian et al., 1997a, 1997b).

Approach

We apply the method of analysis described by Eve et al. (2001) and Sperow et al. (2001) to estimate soil C change between 1982 and 1997 to represent the baseline against which potential soil C change from projected land use changes are compared. Baseline and potential soil C stocks were calculated using the IPCC inventory factors in conjunction with crop rotation and soil information derived from 1997 National Resources Inventory (NRI) data (Nusser and Goebel, 1997). While the IPCC inventory method is comprehensive in accounting for GHG sinks and sources, we used it only to estimate soil C stocks and flows that result from land-use (crop rotations, increased CRP, etc.) and tillage changes on agricultural cropland. The 1997 NRI data were used to identify the 1982 and 1997 baseline crop management systems. The proportion of conventional, reduced and no-till production were derived from personal communications (D. Towery) with the Conservation Technology Information Center (CTIC). We address only the top 30 cm of mineral soils in this analysis, i.e. cultivated organic soils are not considered.

The methods developed by IPCC for inventorying greenhouse gas emissions address the effects of agriculture, industry, energy, waste and land use change. Chapter 5 (Land Use Change and Forestry) addresses land use change and accounts for terrestrial carbon storage in plant biomass and soils (IPCC, 1997c). A series of factors (base, input and tillage) assigned based on climate, soil type, disturbance history, tillage intensity, and productivity (C input rate) are used to estimate changes in soil C stocks from land use and land management practices over a twenty year inventory period (IPCC, 1997b). The IPCC method identifies the change in soil C from a land use or tillage change between the first and last year of the inventory period. Soil C stock is a function of soil C under native vegetation and changes in land use and land management.

Soil C stock is a function of the area in each climate-soil-land use/management category, soil C under native vegetation, and the IPCC base, tillage and input factors. Soil C stocks at the beginning and end of the inventory period were calculated for each climate-soil-land use/management category (see Sperow et al. 2001). The total change in soil C for each climatic region is the sum of soil C stock for each land use category within the region at the end of the inventory period minus the soil C stocks at the beginning of the inventory period. Soil C stocks were then converted to annual rates of change (MMTC yr^{-1}) for the fifteen-year inventory period.

The total soil C sequestration potential for U.S. agricultural soils was estimated by iteratively incorporating potential land use and land management changes. We analyzed soil C sequestration of potential activities in the following order: conversion of HEL to set-aside, inclusion of winter cover crops, reduced fallow systems, and reduced tillage intensity. Thus, soil C in cropland set aside from crop production cannot be increased through reduced tillage, reduced fallow periods, or increased cropping intensity. This method allows the soil C sequestration rates on cropland to be additive.

The CTIC considers no-till, mulch till, strip till, and ridge till, or activities that retain at least 30% residue, conservation tillage (CTIC, 1998). Potential adoption of conservation tillage practices on U.S. cropland have been estimated at 50-60% (Crosson, 1981), 72% (Office of Technology Assessment, 1982), 63-82% (Schertz, 1988), and 95% (USDA, 1975) by 2010. We analyzed the increased soil C from adoption of no-till on all cultivated cropland because we were interested in the total biophysical potential soil C gains from conservation tillage.

Results

The areas of cropland under conventional, reduced, no-till and CRP in 1997 are included in Table 1 along with estimated annual rate of soil C change between 1982 and 1997 by climatic region following the methodology of Eve et al. (2001). Conventional tillage occurred on 64.9%, reduced tillage on 27.2%, and no-till on 7.9% of hectares under agricultural production in 1997. The crop rotation, land-use, and tillage changes between

1982 and 1997 resulted in total soil C sequestration of 20.2 MMTC yr^{-1} for mineral soils, which represents the baseline for this analysis.

Soil C increases of 5.3 MMTC yr^{-1} from existing CRP enrollments were estimated using the IPCC method. This is lower than estimates by Follet et al. (2001; 7.6-11.5 MMTC yr^{-1}), and within the range of Paustian et al. (2000; 5.8 MMTC yr^{-1} (mean simulated rate of accumulation of below ground C)), Lal et al. (1998; 5-11 MMTC yr^{-1}) and Gebhart et al. (1994; 1.85-29.3 MMTC yr^{-1}). Converting remaining HEL (HEL not removed from crop production by CRP) to perennial grass, or other similar 'set-aside' program, has the potential of increasing soil C accumulations by 10.9 MMTC yr^{-1} (Table 2) over baseline conditions. Baseline CRP enrollment was 13.2 Mha, thus converting all HEL to grassland or to a set-aside program such as CRP would remove an additional 25.8 Mha from crop production.

The addition of a winter cover crop to crop rotations provides a potential annual soil C increase of 22.9 MMTC yr^{-1} (Table 2). The CTM and WTM climatic regions contribute all of the potential increases in annual soil C sequestration. Our soil C estimate is higher than the 10.2 MMTC yr^{-1} from Lal et al. (1998) primarily because they included winter cover crops only in regions with corn and soybeans. Potential soil C gains of 3.2 MMTC yr^{-1} were projected when all summer fallow operations are eliminated. The temperate, moist (CTM and WTM) climatic regions provide the highest increases at 2.1 MMTC yr^{-1}, followed by the WTD region at nearly 0.6 MMTC yr^{-1} (Table 2). Lal et al. (1998) estimated increases in soil C from reduced fallow operations of 1.9 MMTC yr^{-1}.

Elimination of conventional and reduced tillage with full adoption of no-till provides potential soil C sequestration increases of over 30.3 MMTC yr^{-1}. The net gain (over baseline conditions) of soil C sequestration from increased adoption of reduced tillage and no till operations is largest in the temperate, moist (CTM and WTM) climatic zones. Complete adoption of no-till management increases soil C by 11.9 MMTC yr^{-1} in the CTM and 14.1 MMTC yr^{-1}in the WTM climatic regions (Table 4). These climatic regions account for nearly 86% of the net increase in soil C when no-till is adopted for all crop systems. The IPCC inventory method provided soil C sequestration rates within the 24-40 MMTC yr^{-1} range estimated by Lal et al. (1998) from conservation tillage.

When all activities are implemented simultaneously, U.S. agricultural soils are estimated to have the potential to increase soil C by 67.3 MMTC yr^{-1}. Every MLRA that contains cultivated cropland and each IPCC climatic region show a positive net increase in soil C (Figure 1). The MLRAs with no change in soil C from potential land use and land management change contain either zero or very little cropland area (0.003% of all conterminous U.S. cropland) and represent a small area relative to the remainder of the country (3%). These MLRAs are dominated by sandy and low activity mineral soils (nearly 80% of the area) and are in cool climatic regions (over 90% of the area).

Benefits

The soil C sequestration rates derived using the IPCC method approximate the upper bound of what may be expected to occur given the soils, climate, tillage, and crop rotation on agricultural soils. These data address all U.S. agricultural soils, and may therefore be used to analyze the economic feasibility of soil C sequestration. The IPCC inventory method allows analysts to determine which regions of the country may provide the greatest increase in soil C, and identify the crop management systems that are most effective at increasing soil C.

Future Activities

For our analyses we used the default values for estimates of soil carbon stocks under native vegetation and the base, input, and tillage factors contained in the IPCC inventory documentation. The default factors were derived from published literature and intended for application anywhere in the world. Literature derived values for soil C stocks under native vegetation and the influence of agricultural activities on those stocks are highly variable. This variability may influence how well the default factors represent the soil C fluxes of the specific country under analysis. We are presently assessing the uncertainty of the specific application of the IPCC method to U.S. agricultural soils, and developing alternative factors that are representative of U.S. agricultural soils. These new data, combined with the IPCC inventory method will allow us to identify a range of values for current and potential soil C sequestration.

One shortcoming of the IPCC inventory method is that it only accounts for changes in C stocks that result from changes during that inventory period. If there is no land use or management change during the inventory period, soil C at the site is considered to be in steady state whether it is in no-till or conventional tillage. We are using the Century model to simulate soil C sequestration over the same agricultural soils with the same crop rotations, tillage events, and climate to provide additional information about the effect of long term cropping activities. In addition, a comparison of Century and IPCC outcomes may provide insights into areas that may require additional research.

We are also analyzing the economic feasibility of soil C sequestration on U.S. agricultural soils using IPCC and Century derived soil C sequestration rates and regional economic models. These analyses will estimate the potential costs of soil C sequestration and identify policy prescriptions that will encourage agricultural practices that increase soil C sequestration.

REFERENCES

Allmaras, R.R., H.H. Schomberg, C.L. Douglas Jr., and T.H. Dao. 2000. Soil organic carbon sequestration potential of adopting conservation tillage in U.S. croplands. *J. Soil Water Conserv.* 55(3): 365-373.

Bruce, J.P., M. Frome, E. Haites, H. Janzen, R. Lal, and K. Paustian. 1999. Carbon sequestration in soils. *J. Soil and Water Conserv.* 54:382-389.

Cole, C.V., K. Flach, J. Lee, D. Sauerbeck, and B. Stewart. 1993. Agricultural sources and sinks of carbon. *Water, Air and Pollution.* 70:111-122.

Crosson, P. 1981. Conservation tillage and conventional tillage: A comparative assessment. Soil Cons. Soc. Am., Ankeny, IA.

CTIC. 1998. 1998 Crop residue management executive summary. Conservation Technology Information Center, West Lafayette, IN.

Davidson, E.A. and I.L. Ackerman. 1993. Changes in soil carbon inventories following cultivation of previously untilled soils. *Biogeochemistry*. 20:161-193.

Dick, W.A., R.L. Blevins, W.W. Frye, S.E. Peters, D.R. Christenson, F.J. Pierce, and M.L. Vitosh. 1998. Impacts of agricultural management practices on C sequestration in forest-derived soils of the eastern Corn Belt. *Soil and Tillage Research*. 47: 235-244.

Eve, M.D., K. Paustian, R. Follett, and E.T. Elliot. 2001. A national inventory of changes in soil carbon from National Resources Inventory data. *In.* R. Lal, J.M. Kimble, R.F. Follett, B.A. Stewart (eds.), Assessment methods for soil carbon. CRC Publishers, Boca Raton, FL.

Follett, R.F., S.E. Samson-Liebig, J.M. Kimble, E.G. Pruessner, and S.W. Waltman. 2001. Carbon sequestration under the CRP in the historic grassland soils in the USA. In: R.Lal and K. McSweeney (eds) "Soil Management for Enhancing Carbon Sequestration," SSSA Special Publication, Madison, WI. (*in press*)

Gebhart, D.L., H.B. Johnson, H.S. Mayeux, and H.W. Polley. 1994. The CRP increases in soil organic carbon. *J. Soil Water Conserv*. 49:488-492.

IPCC. 1997a. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reporting Instructions (Volume 1). Houghton, J.T., L. G. Meria Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, and B.A. Callender (Eds.). Intergovernmental Panel on Climate Change.

IPCC 1997b. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Workbook (Volume 2). Houghton, J.T., L. G. Meria Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, and B.A. Callender (Eds.). Intergovernmental Panel on Climate Change.

IPCC 1997c. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories Reference Manual (Volume 3). Houghton, J.T., L. G. Meria Filho, B. Lim, K. Treanton, I. Mamaty, Y. Bonduki, D.J. Griggs, and B.A. Callender (Eds.). Intergovernmental Panel on Climate Change.

Lal, R., J. Kimble, R.F. Follett, and C.V. Cole. 1998. The Potential for U.S. Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Sleeping Bear Press, Ann Arbor, MI. 128 pp.

Lal, R., R.F. Follett, J. Kimble, and C.V. Cole. 1999. Managing U.S. cropland to sequester carbon in soil. *J. Soil Water Conserv.* 54:374-381.

Mann, L.K. 1985. A regional comparison of carbon in cultivated and uncultivated Alfisols and Mollisols in the central United States. *Geoderma*. 36: 241-253.

Nusser, S.M. and J.J. Goebel. 1997. The National Resources Inventory: a long-term multi-resource monitoring programme. *Environ. and Ecol. Statistics.* 4:181-204.

Office of Technology Assessment. 1982. Impacts of technology on U.S. cropland and rangeland productivity. Cong. Bd. 97th Cong., Washington, D.C.

Paustian, K., O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. Van Noorwijk, and P.L. Woomer. 1997a. Agricultural Soils as a sink to mitigate CO_2 emissions. *Soil Use and Mgt.* 13:230-244.

Paustian, K., H.P. Collins, and E.A. Paul. 1997b. Management controls on soil carbon. pp 15-49. *In*: Paul, E.A., K. Paustian, E.T. Elliot, and C.V. Cole (eds) Soil Organic Matter in Temperate Agroecosystems: Long-Term Experiments in North America. CRC Press, Boca Raton, FL.

Paustian, K., E.T. Elliott, K. Killian, J. Cipra, G. Bluhm, and J.L. Smith. 2000. Modeling and regional assessment of soil carbon: A case study of the Conservation Reserve Program. *In* R. Lal and K. McSweeney (eds) Soil Management for Enhancing Carbon Sequestration. SSSA Special Publ., Madison WI. (*in press*)

Schertz, D.L. 1988. Conservation tillage: An analysis of acreage projections in the United States. J. Soil Water Conserv. 43: 256-258.

Sperow, M., M. Eve, and K. Paustian. 2001. Potential soil C sequestration on U.S. agricultural soils. (*In Review*)

U.S.D.A., Office of Planning and Evaluation. 1975. Minimum tillage: A preliminary technology assessment. Washington, D.C.

Table 1. Baseline areas of conventional, reduced, no-tillage and CRP for the conterminous U.S. by climatic region with estimated baseline changes (1982-1997) in soil C from IPCC inventory analysis (annual average rate of change).

Climatic Region1	Conventional Tillage	Reduced Tillage	No Tillage	CRP[2]	Total Soil C δ^3
	--------------------Thousand Hectares-------------------				Soil C Sequestration (MMTC yr^{-1})
CTD	5,500	3,200	1,100	2,300	1.2
CTM	30,400	15,900	3,900	4,100	5.1
STD	900	100	2	80	0.2
STM	1,500	400	20	5	-0.7
WTD	10,900	2,100	200	2,400	1.2
WTM	31,200	11,900	4,500	4,300	13.2
Total	80,400	33,700	9,700	13,100	20.2

1 CTD = Cool Temperate Dry; CTM = Cool Temperate Moist; STD = Subtropical Dry; STM = Subtropical Moist; WTD = Warm Temperate Moist; WTM = Warm Temperate Moist.

2 CRP = Conservation Reserve Program.

3 δ = annual average rate of change.

4 The change in soil C from activities other than reduced tillage intensity.

Table 2. Potential change in soil C resulting from elimination of summer fallow, conversion of highly erodible land (HEL) to set-aside (a program like CRP), a winter cover crop is included in the crop rotation or complete adoption of no-till.

		Potential Land Management Changes			
Climatic Region[1]	Baseline	Eliminate Summer Fallow	HEL[2] to Set-Aside[3]	Addition of Winter Cover Crop	100% Adoption of No-Till
	---------------------------- Soil C Sequestration (MMTC yr^{-1}) ----------------------------				
CTD	1.3	0.4	1.8	0.0	0.6
CTM	5.0	0.9	3.2	11.3	11.9
STD	0.2	0.0	0.3	0.0	0.2
STM	-0.7	0.1	0.1	0.0	1.2
WTD	1.2	0.6	1.6	0.0	2.3
WTM	13.2	1.2	4.0	11.6	14.1
Total	20.2	3.2	10.9	22.9	30.3

[1] CTD = Cool Temperate Dry; CTM = Cool Temperate Moist; STD = Subtropical Dry; STM = Subtropical Moist; WTD = Warm Temperate Moist; WTM = Warm Temperate Moist.

[2] HEL = Highly Erodible Land.

[3] Set-Aside is cropland removed from crop production and planted to perennial grass.

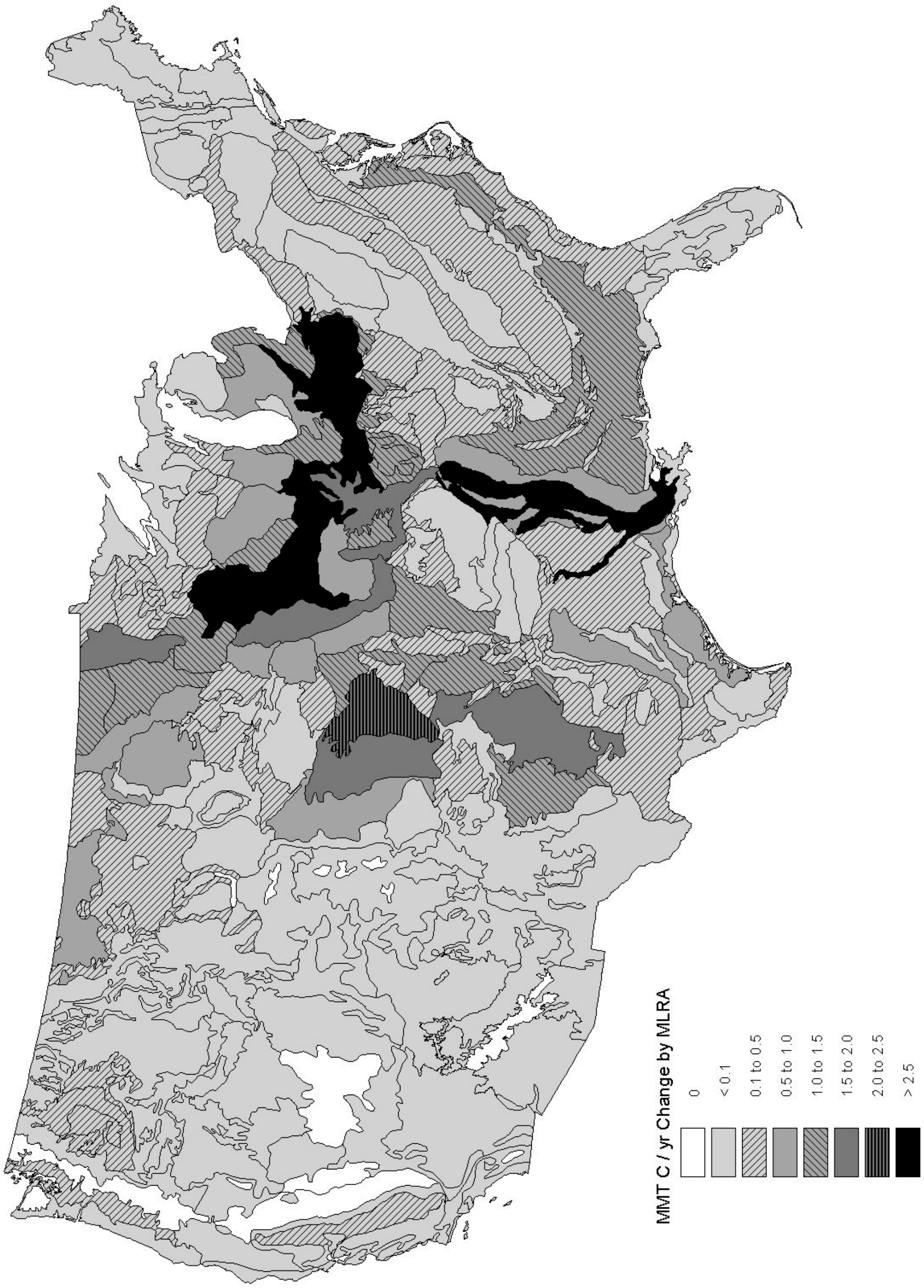

Figure 1. Soil C increase estimated using the IPCC inventory method when all cultivated cropland is converted to no-till production, highly erodible land is converted to grassland, winter cover crops are included in the crop rotation, and bare summer fallow operations are eliminated, delineated by Major Land Resource Region (MLRA).