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National-scale estimation of changes in soil carbon stocks on agricultural lands

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"Capsule": *Changes in land use and management have resulted in a net gain of 21.2 MMT (million metric tons) of carbon per year in US agricultural soils between 1982 and 1997.*

Abstract

Average annual net change in soil carbon stocks under past and current management is needed as part of national reporting of greenhouse gas emissions and to evaluate the potential for soils as sinks to mitigate increasing atmospheric CO_2. We estimated net soil C stock changes for US agricultural soils during the period from 1982 to 1997 using the IPCC (Intergovernmental Panel on Climate Change) method for greenhouse gas inventories. Land use data from the NRI (National Resources Inventory; USDA-NRCS) were used as input along with ancillary data sets on climate, soils, and agricultural management. Our results show that, overall, changes in land use and agricultural management have resulted in a net gain of 21.2 MMT C year^{-1} in US agricultural soils during this period. Cropped lands account for 15.1 MMT C year^{-1}, while grazing land soil C increased 6.1 MMT C year^{-1}. The land use and management changes that have contributed the most to increasing soil C during this period are (1) adoption of conservation tillage practices on cropland, (2) enrollment of cropland in the Conservation Reserve Program, and (3) cropping intensification that has resulted in reduced use of bare fallow.

Keywords: Carbon sequestration; Global change; Land use change; IPCC inventory; Carbon dioxide (CO_2); Greenhouse gas

1. Introduction

Levels of CO_2 and other greenhouse gases in the atmosphere have been increasing (IPCC, 2001). Rising concern over the impact that these gases may have on world climate systems has resulted in increased awareness of the global carbon cycle. International negotiations are aimed at reducing the level of CO_2 in the atmosphere (UNFCCC, 1997). One means of removing CO_2 from the atmosphere is using growing plants to convert atmospheric CO_2 to usable food, fiber, and excess biomass, and improve the conversion of the excess biomass to soil organic C. In photosynthesis, plants utilize atmospheric CO_2, and store organic C within above and below ground biomass. While field studies have long documented the ability of plants to transport C from the atmosphere to the soil, national level inventories that quantify the amount of C being stored are relatively new, and necessary for any type of full C accounting system. The Intergovernmental Panel on Climate Change (IPCC) has developed an inventory method that can be applied by United Nations Framework Convention on Climate Change (UNFCCC) members to conduct national-level greenhouse gas inventories. We used the IPCC method to conduct an inventory of soil organic C for cropland and grazing land soils of the USA for the period 1982 to 1997.

The inventory methods developed by IPCC are comprehensive, and address anthropogenic influences on sources and sinks of greenhouse gases, such as agricultural, industrial, energy, waste, and forestry and land use activities. The IPCC section dealing with land use change accounts for changes in terrestrial carbon storage in plant biomass as well as in soils. Because CO_2 is exchanged between plant/soil systems and the atmosphere through the processes of photosynthesis and respiration, net changes in plant/soil C stocks can be equated to net changes in CO_2 emissions. In cropping

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and grazing systems much of the above ground biomass is either removed by harvest or returned to the soil. Therefore, this analysis focuses on changes in soil carbon stocks related to changes in land use and/or agricultural management practices. Documentation related to the inventory methods for land use and management change can be found in IPCC Workbook Module 5 (Land-Use Change and Forestry; IPCC, 1997b) and Reference Manual Chapter 5 (Land-Use Change and Forestry; IPCC, 1997c).

The IPCC inventory method is a practical, first-order approach using simple assumptions about the effects of land use change on carbon stocks, and then applying those assumptions to estimate changes in carbon stocks resulting from land use change over the inventory period. A series of coefficients based on climate, soil type, disturbance history, tillage intensity, productivity and residue management are used to estimate changes in soil carbon (IPCC, 1997b). The default method applies to the upper 30 cm of the soil profile.

The IPCC method is general in order to facilitate broad application by Parties to the UNFCCC, but flexible enough that more detailed analysis can be conducted if data are available. Information is organized in a series of worksheets, each related to a different source of carbon flux. The worksheets contain the formulas necessary to compute soil carbon storage (IPCC, 1997b). For the most basic application of the inventory, the investigator needs only the estimated area under each land use and/or management system at the beginning and end of the inventory period. The IPCC authors gleaned information from research literature to establish default values for native carbon levels and changes in carbon stocks under different land use and management change scenarios. If more detailed information is available for the country being inventoried, native carbon values and change factors can be adjusted to make the inventory as accurate as possible.

In the USA, detailed data are available that are well suited to application of the IPCC approach. Every five years, the US Department of Agriculture Natural Resources Conservation Service (USDA-NRCS, formerly the Soil Conservation Service) collects detailed land use, land cover, and other natural resource related data from an extensive network of permanent sampling sites across the USA as part of the National Resources Inventory (NRI). Each year, the Conservation Technology Information Center (CTIC) Crop Residue Management Survey records changes in tillage management including trends from conventional tillage practices to conservation tillage or no-till (CTIC, 1998). Daily and monthly climatic data are recorded at a nationwide network of weather stations. Through manipulation of these and other data, we estimated changes in US agricultural soil C stocks.

2. Materials and methods

Land use change is realized through activities such as rangeland being converted to cropland, cropland being converted to pasture or set-aside, or agricultural land being planted into forest. Changes in agricultural management include changing cropping systems (such as shifting from a corn/soybean rotation to a corn/hay rotation) or tillage management practices (such as shifting from conventional tillage to no-till). Changes in land use and agricultural land management have been and are currently occurring in the United States (Kellogg et al., 1994; CTIC, 1998; Paustian et al., 1998; Allmaras et al., 2000; NRCS, 1999b). These changes significantly impact soil carbon stocks (Paustian et al., 1997a, 1997b, 2001; Buyanovsky and Wagner, 1998; Bruce et al., 1999; Houghton et al., 1999; Lal et al., 1999; Follett et al., 2001).

2.1. Input data

The primary data requirements for the IPCC method deal with the land use and land management changes over time. However, information is also needed to stratify these changes according to climate and soil type. Under the IPCC approach, climate is divided into eight distinct categories based upon average annual temperature, average annual precipitation, and the length of the dry season (IPCC, 1997c). Six of these climatic categories occur in the conterminous US and Hawaii (Eve et al., 2001). Soils in the IPCC method are defined by taxonomic soil order. Orders are grouped into one of six classes based upon texture, morphology, and ability to store organic matter (IPCC, 1997a, c). Five of the categories are mineral soil (high clay activity mineral soils, low clay activity mineral soils, sandy, volcanic, and aquic soils) and one is organic soil (IPCC, 1997c). For each of the five mineral soil classes, the IPCC method provides default estimates of C stocks under native (i.e. pre-agricultural) conditions (IPCC, 1997c). For the organic soils, the IPCC method does not assign C stocks and change factors, but rather estimates annual losses of soil C directly. The types of land use and/or land management change are defined specifically for the country being inventoried. It is important only that the systems identified capture the changes over the previous 20 years (IPCC, 1997c).

For this type of inventory, the USA has suitable data sources available for the entire country. We utilized the most detailed national-level data currently available in the USA, starting with the Major Land Resource Areas (MLRA; NRCS, 1981) as our basic spatial unit. MLRAs were originally delineated by the USDA-NRCS in the 1960s as a tool to assist land managers and land use planners. Each MLRA represents a geographic unit with relatively similar soils, climate, water resources, and land uses (NRCS, 1981).

We grouped the MLRAs by climate according to the IPCC climate categories. Climate in the USA is monitored through an extensive network of National Weather Service (NWS) cooperative weather stations. Other national agencies also maintain specific climate databases such as the USDA-NRCS Snotel network and the National Climatic Data Center (NCDC) Global Gridded Upper Air Statistics database. The PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping program has combined the 1961–1990 averages from each of these sources with topographic information derived from digital elevation models (DEM) to generate gridded (4×4 km grid cells) estimates of temperature and precipitation for the USA (Daly et al., 1994; Daly et al., 1998). Average annual precipitation and average annual temperature were derived for each MLRA from PRISM model outputs. These averages were used to aggregate the nearly 180 MLRAs that make up the conterminous USA into the six prescribed IPCC climatic zones represented within the USA (Fig. 1).

We obtained the dominant taxonomic soil order for each NRI point by querying the soils database that accompanies the NRI data (NRCS, 1999a). Soil orders were grouped into the six broad IPCC soil categories. The five IPCC categories of mineral soils were delineated based upon their ability to support biomass growth and to capture and stabilize soil C. For these soils, a C stock was computed at the beginning and end of the inventory period, with the change in stocks being the difference between the two (IPCC, 1997b). Because organic soils are made up of deep (>30 cm) layers of organic material, IPCC does not estimate stocks on these soils. Rather, the IPCC method assigns an annual rate of loss based upon land use (IPCC, 1997b).

Land use and land use change information was derived from the 1997 NRI data. The NRI is a stratified two-stage area sample of over 800,000 points across the USA (Nusser and Goebel, 1997). Each point in the survey is assigned an area weight (expansion factor) based on other known areas and land use information (Nusser and Goebel, 1997). An extensive amount of soils, land use, and land management data are collected during each survey. Nearly all sites are surveyed every 5 years (Nusser et al., 1998). NRI was designed as a tool to assess conditions and trends for soil, water, and related natural resources primarily on non-federal lands of the USA (Kellogg et al., 1994; Nusser and Goebel, 1997).

Because the data points and the information collected have remained fairly constant since 1982, NRI is a useful source for much of the data required for the US soil C inventory. Land use and land management data for 1982 and 1997 were obtained from the NRI (NRCS, 1999a). For the purposes of our research, the land use information in NRI was merged into a combined land use and land management system. Each NRI point was assigned to a system based upon the land use data collected in the 1982 and 1997 surveys as well as the cropping history data recorded for the three years prior to each survey (NRCS, 1999a). Each of the over 800,000 NRI points was assigned an aerial extent based upon the weighted expansion factors discussed earlier.

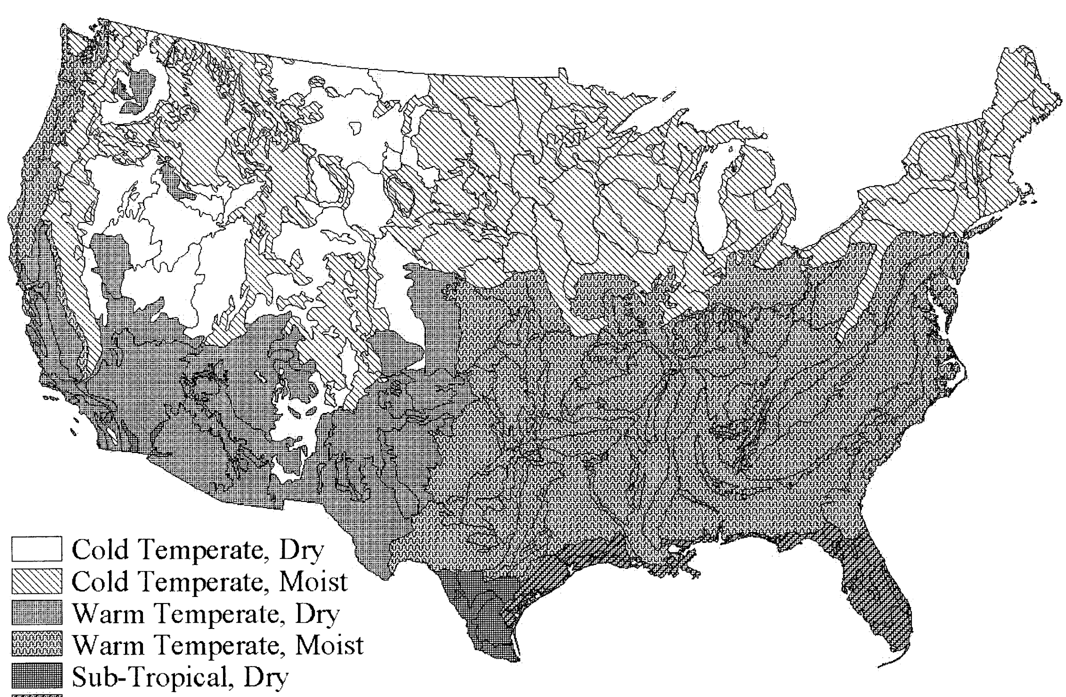

Fig. 1. Map of climate regions based on average annual temperature and precipitation within each NRCS MLRA.

This analysis was performed as part of the USA submission for international climate treaty negotiations (UNFCCC, 2000). The UNFCCC requirements specify a baseline year near 1990. From the NRI data, the 1992 inventory became our baseline year. Because our inventory was only for cropland and grazing land, any NRI points that were not identified as cropland or grazing land in the 1992 and/or 1997 inventory were removed from the analysis.

Data on tillage practices are not adequately reported in the NRI data to facilitate our analysis. Therefore, we utilized tillage data from the Conservation Technology Information Center (CTIC), which conducts annual, county-level surveys of the adoption of conservation tillage management (CTIC, 1998). Each year the CTIC conducts a Crop Residue Management (CRM) survey to estimate the portion of cropland being managed under the various tillage systems. These surveys identify the area of a specific crop planted by tillage system for each survey year, including areas of rotational no-till where one year's crop may be planted into no-till and the following crop planted using tillage (Hill, 2000). The CRM survey does not estimate adoption of continuous no-till. Hence, the areas reported in no-till for a particular year are greater than the areas under continuous no-till. Field experiments suggest that alternating tillage and no-till management eliminates most of the benefits of no-till with respect to soil C stabilization are lost (Pierce et al., 1994; Reicosky, 1997; Stockfisch et al., 1999). Supplemental information from CTIC was required to estimate the adoption of continuous no-till and reduced tillage systems by region for the USA. For this study, use of a specific system for 5 years was considered continuous adoption. CTIC provided these estimates for both 1982 and 1997 to coincide with the years of NRI data being utilized (Dan Towery, personal communication). The continuous no-till estimates are 50–70% lower than the annual estimates from the published CTIC CRM data.

2.2. Data analysis

Changes in soil C were estimated for each NRI point in the conterminous USA and Hawaii that was identified as either cropland or grazing land. To do this, each point was assigned to a climatic region (based on Fig. 1), and the dominant soil order for each point was determined from the soils database associated with the NRI data set. Each point was assumed to represent the number of hectares as estimated by the NRI expansion factor. Each NRI point that was associated with one of the mineral soils was assigned IPCC factor values. The extent of each cultivated cropland site was further separated into relative proportions of conventional tillage, reduced tillage, and no-till hectares by utilizing the information provided by CTIC. Based upon the soil order, land use, agricultural crop rotation, and tillage management in place in 1982, the soil C stock for each point was determined using the IPCC inventory approach and default factor values. Carbon stocks for non-cropland areas were computed as:

$$C_n = ha_n \times SCUN_n \times BF_n \times IF_n \tag{1a}$$

and C stocks for cropland sites were computed as:

$$\begin{aligned} C_n = {} & (haNT_n \times SCUN_n \times BF_n \times IF_n \times TF_{NT}) \\ & + (haRT_n \times SCUN_n \times BF_n \times IF_n \times TF_{RT}) \\ & + (haCT_n \times SCUN_n \times BF_n \times IF_n \times TF_{CT}) \end{aligned} \tag{1b}$$

where: C_n is the estimated 1982 C stock for the area represented by NRI point (n), ha_n is the area (in hectares) associated with point (n) in 1982, $SCUN_n$ is the IPCC default estimate of soil C under native vegetation at point (n) given the climatic zone and soil type at that point, BF_n is the IPCC base factor, or the relative percentage of soil C that has been lost historically by point (n) because of it historical use, and IF_n is the IPCC input factor for point (n), which adjusts soil C levels based upon the level of plant residue, which depends on factors affecting productivity and residue management, such as cropping intensity, irrigation, residue removal, and organic amendments. $haNT_n$ is the hectares related to point (n) that represent no-tillage management systems in 1982, $haRT_n$ is the hectares related to point (n) that represent reduced tillage management systems in 1982, $haCT_n$ is the hectares related to point (n) that represent conventional tillage management systems in 1982, TF_{NT} is the IPCC tillage factor for a no-till system, TF_{RT} is the IPCC tillage factor for a reduced tillage system, and TF_{CT} is the IPCC tillage factor for a conventional tillage system.

The sum of the hectares (haNT), (haRT) and (haCT) in Eq. (1b) for each NRI point equals the area related to that point based on the NRI expansion factor. Carbon stocks for 1997 were computed the same way utilizing the 1997 data on soil order, land use, agricultural crop rotation, and tillage management related to each NRI point.

Once the soil C stocks for the 1982 inventory and the 1997 inventory were completed for each NRI point, the change in C stocks at that point was simply computed as the 1997 stock minus the 1982 stock. The IPCC defaults are designed to estimate changes over a 20-year period. The available NRI data, however, only span 15 years. In order to derive an estimate of change over a 15-year inventory period (rather than the IPCC default 20-year inventory) we scaled the amount of change proportionally, computing change in C stocks for each point and converting to an annual average change over the 15-year period. The annual average change was aggregated by type of land use change, and summed as million metric tons of C per hectare per year (MMT C ha^{-1} $year^{-1}$).

Organic soils are handled separately in the IPCC approach. Organic soils that are under native vegetation are excluded from the inventory under the assumption that they are not significantly affected by human activity. Organic soils that are intensively managed are assigned a default rate of C loss based on land use system and the climatic region where they are located (IPCC, 1997c). Only two types of managed systems are considered: cropland and introduced pasture/forest (IPCC, 1997b). Default C loss rates from croplands established on organic soils are four times greater than loss from pasture and forest plantations on organic soils in the same climatic region (IPCC, 1997b).

3. Results

The NRI data confirm that significant changes in land use have occurred in the USA during the period 1982–1997 (Kellogg et al., 1994; NRCS, 1999b). A few specific changes in land use and agricultural management have resulted in the largest increase in soil C storage nationally. The Conservation Reserve Program (CRP) is a federal program of the 1985 US Food Securities Act intended to take highly erodible cropped land out of agricultural production by planting it back to grass or trees for a 10-year period. Because CRP was implemented as part of the 1985 Farm Bill, there were no CRP hectares at the beginning date of our inventory. As of the 1997 NRI survey, nearly 13.2 Mha (of the 165 Mha US cropland base) were enrolled in CRP (NRCS, 1999a). The soil is not disturbed under CRP and most of the biomass is not removed, so these soils have been shown to increase in C storage (Gebhart et al., 1994; Huggins et al., 1998; Paustian et al., 2001).

The other notable shift between 1982 and 1997 is the adoption of conservation tillage. Schertz (1988) estimated that about 18% of all US cropland was managed under some form of conservation tillage in 1982. By 1998, the adoption of conservation tillage practices had doubled to 36% (CTIC, 1998). When the definition of conservation tillage is relaxed to include what CTIC defines as reduced tillage, the increase is even more dramatic with 26% adoption in 1982 (Schertz, 1988) and 65% adoption in 1998 (CTIC, 1998). As noted earlier, much of the data on tillage systems have been based on annual surveys that do not account for long-term adoption. However, even when the tillage adoption rates presented above are scaled to account for long-term adoption, the relative changes during the inventory period remain substantial. Reducing tillage results in increased soil C because there is less disturbance of the soil surface, and thus, more residue at the surface and less release of soil C as CO_2 (Reicosky, 1997). Also, no-till systems have been shown to result in increased amounts and stability of soil aggregates that aids the soil in stabilizing organic C (Six et al., 1999).

During the inventory period, the use of bare summer fallow declined dramatically. Our interpretation of the NRI data indicates that in 1982, there were approximately 20 Mha of agricultural rotations that included bare summer fallow. By the 1997 inventory, the area of bare summer fallow decreased to about 12 Mha. The fallow period can result in large losses of soil C to the atmosphere, especially if extensive tillage is used for weed control. Eliminating or reducing the use of bare fallow may result in increased biomass production and decreased soil disturbance, increasing the amount of C stored in the soil.

One final management shift that was not considered in the previous inventory work of Eve et al. (2001) is the application of organic manure to managed grazing lands. Follett et al. (2001) estimated that manure may be applied to as much as 25% of managed pasture hectares in the USA. Application of animal manure greatly enhances soil organic C contents both through the C content of the manure and the increased biomass production resulting from the added nitrogen. We used a conservative estimate of 15% increase in pasture area receiving supplemental organic manure between 1982 and 1997 and assumed that no manure is being applied to native rangeland.

Based on our application of the IPCC inventory methods, we estimate net soil C sequestration on USA agricultural lands at 21.2 MMT C $year^{-1}$ average over the 15-year inventory period 1982 to 1997 (Table 1). Of this total, 6.1 MMT C $year^{-1}$ is sequestered on grazing lands while 15.1 MMT C $year^{-1}$ is stored in cropland soils. These net values account for the emissions (negative soil C storage) from organic soils as well as the sequestration (positive soil C storage) on mineral soils (Table 1; Fig. 2).

Our cropland estimate of 15.1 MMT C $year^{-1}$ is an estimate of actual changes in soil C storage resulting from documented changes in land use and cropland management. Lal et al. (1998, 1999) estimate the potential of cropland soil to sequester C between 75 and 208 MMT C $year^{-1}$, and Bruce et al. (1999) estimate this potential at about 75 MMT C $year^{-1}$ (Fig. 3). These projections of potential sequestration are based on a "full" implementation of management improvements that considerably exceed levels used in the current analysis. Furthermore, Lal et al. (1998, 1999) include the potential development of bio-fuel technologies, improved erosion control, wetland restoration, and other soil management strategies not included in our analysis.

Table 1
Annual changes in C stocks by broad land use activity based upon IPCC analysis using the National Resources Inventory data (NRCS, 1999a)

Activity	Area (ha)[a]	Annual numbers for 1997			
		Chg min soil (MMT C)	Chg org soil (MMT C)	Tot ann chg (MMT C)	Uncertainty[b]
Cropland[c]	168,277,993	20.7	−5.6	15.1	±50%
Grazing land[d]	276,138,354	6.6	−0.5	6.1	±50%

[a] Area in each land use category is based upon analysis of the 1997 NRI, and includes the conterminous USA and Hawaii.
[b] Uncertainty for this analysis is an estimate only, rigorous uncertainty analysis is currently being conducted.
[c] Cropland includes CRP, hay, and annual cropping systems.
[d] Grazing lands include rangeland and continuous pasture. Federal grazing lands were added based on Sobecki et al. (2001) (58.7 Mha). These lands are included in the base, but assumed to be steady state (no net change in soil C).

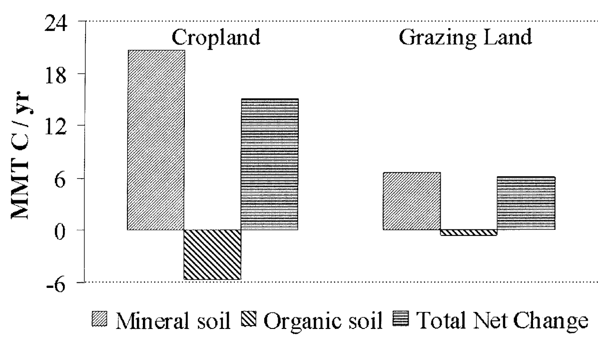

Fig. 2. Changes in carbon storage on US cropland and grazing land estimated using the IPCC inventory technique and NRCS National Resources Inventory data. (Uncertainty is currently being analyzed, but has been estimated at ±50% of the Total Net Change).

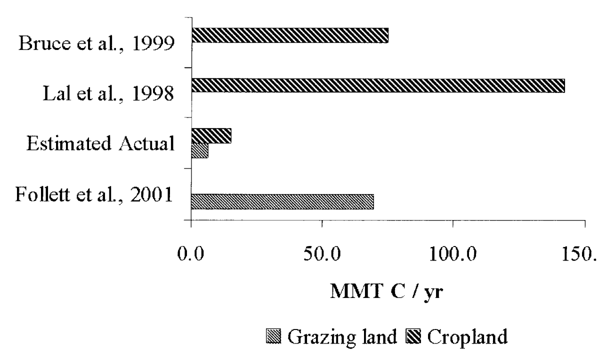

Fig. 3. Estimated actual C storage compared to recently published estimated potentials of agricultural soil C storage. (Uncertainty of the "Estimated Actual" is currently being analyzed, but has been estimated at ±50%. Lal et al. (1998) and Follett et al. (2001) are mean values taken from a range of potentials).

Our estimate of current soil C sequestration on grazing lands is 6.1 MMT C year^{-1}. Follett et al. (2001) estimate a potential for improved grazing land management to increase soil C by 29.5 to 110 MMT C year^{-1} during a 25-year period (Fig. 3). This potential is again based on assumptions of widespread improvements in fertility, water, and grazing management, and land conversion and restoration (Follett et al., 2001). Our estimate is a best approximation of what actually happened in many of these categories during the period from 1982 to 1997, which is far short of the potential soil C storage ability. Follett et al. (2001) include grazing management and other practices that our analysis does not consider.

4. Discussion

The IPCC inventory approach was designed for broad application by signatory nations to the UNFCCC. It accounts for changes in C stocks resulting from changes in land use. It also accounts for changes in land management such as cropping practices and tillage systems. The approach addresses only "anthropogenic" sinks and sources—those occurring as a result of human management or impact on the landscape. Therefore, the approach does not consider changes in C stocks on "unmanaged" native ecosystems or from change that occurred prior to the initial year of the inventory.

The IPCC inventory method has been designed to minimize uncertainty related to the definitions and methodology (IPCC, 1997a). However, the IPCC default factor values and each of the input data sets have uncertainty that gets passed through the analysis to the final inventory estimates. Because of limited data and the spatial variability of soils, it is extremely difficult to objectively quantify the level of uncertainty in this type of analysis (Cannell et al., 1999; Houghton et al., 1999). A recent IPCC report indicates that it is often necessary to use expert judgement in evaluating uncertainty when measured data are not available (IPCC, 2000). The inventory Reference Manual (IPCC, 1997a) reports a relative level of uncertainty for land use change activity of ±50%. Furthermore, the IPCC authors conclude that uncertainty is likely to be less for trends over time than for absolute stock values from a given point in time (IPCC, 2000). We believe that ±50% is a reasonable initial estimate of uncertainty in our analysis. We are currently conducting a quantitative assessment of uncertainty for this analysis. For a more detailed explanation of possible sources of uncertainty in this analysis, see Eve et al. (2001), and IPCC (1997a, 2000).

5. Conclusions

Our results show that the net effect of land use and management changes on agricultural soils have led to an increase in soil C storage. There are several possible explanations for a C sink in agricultural soils. Some include: (1) many upland agricultural soils having been in production long enough that they are approaching a new steady state C level (Cole et al., 1993), (2) crop yields (and crop biomass) increasing substantially since the 1940s (Allmaras et al., 1998; Buyanovsky and Wagner, 1998), (3) increased adoption of conservation tillage practices (Kern and Johnson, 1993; Lal and Kimble, 1997; Allmaras et al., 2000), and (4) conversion of significant areas of annual cropland to grass and trees through the CRP (Gebhart et al., 1994; Lal et al., 1999).

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References

Allmaras, R.R., Wilkins, D.E., Burnside, O.C., Mulla, D.J., 1998. Agricultural technology and adoption of conservation practices. In: Pierce, F.J., Frye, W.W. (Eds.), Advances in Soil and Water Conservation. Sleeping Bear Press, Chelsea, MI, pp. 99–158.

Allmaras, R.R., Schomberg, H.H., Douglas, C.L., Dao, T.H., 2000. Soil organic carbon sequestration potential of adopting conservation tillage in US croplands. Journal of Soil and Water Conservation 55, 365–373.

Bruce, J.P., Frome, M., Haites, E., Janzen, H., Lal, R., Paustian, K., 1999. Carbon sequestration in soils. Journal of Soil and Water Conservation 54, 382–389.

Buyanovsky, G.A., Wagner, G.H., 1998. Carbon cycling in cultivated land and its global significance. Global Change Biology 4, 131–141.

Cannell, M.G.R., Milne, R., Hargreaves, K.J., Brown, T.A.W., Cruickshank, M.M., Bradley, R.I., Spencer, T., Hope, D., Billett, M.F., Adger, W.N., Subak, S., 1999. National inventories of terrestrial carbon sources and sinks: The UK experience. Climatic Change 42, 505–530.

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

CTIC, 1998. 1998 Crop Residue Management Executive Summary. Conservation Technology Information Center, West Lafayette, IN.

Daly, C., Taylor, G.H., Gibson, W.P., Parzybok, T., Johnson, G.L., Pasteris, P.A., 1998. Development of high-quality spatial datasets for the United States. In: Proc. 1st International Conference on Geospatial Information in Agriculture and Forestry, 1–3 June, 1998. Lake Buena Vista, FL, pp. I-512–I-519.

Daly, C., Neilson, R.P., Phillips, D.L., 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33, 140–158.

Eve, M.D., Paustian, K., Follett, R., Elliott, E.T., 2001. A national inventory of changes in soil carbon from National Resources Inventory data. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Methods of Assessment of Soil Carbon. CRC Press, Boca Raton, FL, pp. 593–610.

Follett, R.F., Kimble, J.M., Lal, R., 2001. The potential of US grazing lands to sequester soil carbon. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of US Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton, FL, pp. 401–430.

Gebhart, D.L., Johnson, H.B., Mayeux, H.S., Polley, H.W., 1994. The CRP increases soil organic carbon. Journal of Soil and Water Conservation 49, 488–492.

Hill, P.R., 2000. Continuous use of no-till cropping systems in the Corn Belt. In: Speaker and Poster Abstracts, Abstract 34. Conference on: Carbon: Exploring the Benefits to Farmers and Society. Des Moines, IA, 29–31 August 2000. Available at: http://www.cvrcd.org/carbon.htm.

Houghton, R.A., Hackler, J.L., Lawrence, K.T., 1999. The US carbon budget: contributions from land-use change. Science 285, 574–578.

Huggins, D.R., Allan, D.L., Gradner, J.C., Karlen, D.L., Bezdicek, D.F., Alms, M.J., Flock, M., Miller, B.S., Staben, M.L., 1998. Enhancing carbon sequestration in CRP-managed land. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 323–350.

IPCC. 1997a. Revised 1996 IPCC guidelines for national greenhouse gas inventories reporting instructions (Vol. 1). In: Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J., Callender, B.A. (Eds.) Intergovernmental Panel on Climate Change.

IPCC. 1997b. Revised 1996 IPCC guidelines for national greenhouse gas inventories workbook (Vol. 2). In: Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J., Callender, B.A. (Eds.) Intergovernmental Panel on Climate Change.

IPCC. 1997c. Revised 1996 IPCC guidelines for national greenhouse gas inventories reference manual (Vol. 3). In: Houghton, J.T., Meira Filho, L.G., Lim, B., Treanton, K., Mamaty, I., Bonduki, Y., Griggs, D.J., Callender, B.A. (Eds.) Intergovernmental Panel on Climate Change.

IPCC. 2000. Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. Intergovernmental Panel on Climate Change.

IPCC. 2001. Climate Change 2001: The Scientific Basis. Summary for Policymakers (Third Assessment Report). Intergovernmental Panel on Climate Change. Geneva, Switzerland.

Kellogg, R.L., TeSelle, G.W., Goebel, J.J., 1994. Highlights from the 1992 national resources inventory. Journal of Soil and Water Conservation 49, 521–527.

Kern, J.S., Johnson, M.G., 1993. Conservation tillage impacts on national soils and atmospheric carbon levels. Soil Science Society of America Journal 57, 200–210.

Lal, R., Follett, R.F., Kimble, J., Cole, C.V., 1999. Managing US cropland to sequester carbon in soil. Journal of Soil and Water Conservation 54, 374–381.

Lal, R., Kimble, J., Follett, R.F., Cole, C.V., 1998. The Potential of US Cropland to Sequester Carbon and Mitigate the Greenhouse Effect. Sleeping Bear Press, Chelsea, MI.

Lal, R., Kimble, J.M., 1997. Conservation tillage for carbon sequestration. Nutrient Cycling in Agroecosystems 49, 243–253.

NRCS, 1981. Land Resource Regions and Major Land Resource Areas of the United States. USDA Agriculture Handbook 296. United States Department of Agriculture, Natural Resources Conservation Service (formerly Soil Conservation Service). National Soil Survey Center, Lincoln, NE, USA.

NRCS. 1999a. 1997 National Resources Inventory Digital Data. United States Department of Agriculture, Natural Resources Conservation Service (formerly Soil Conservation Service). Washington, DC. NOTE: At the time of this analysis, NRCS was revising the 1997 NRI data. Therefore, the data and the analysis presented here should be considered preliminary.

NRCS. 1999b. Summary Report: 1997 National Resources Inventory. United States Department of Agriculture, Natural Resources Conservation Service.

Nusser, S.M., Goebel, J.J., 1997. The national resources inventory: a long-term multi-resource monitoring programme. Environmental and Ecological Statistics 4, 181–204.

Nusser, S.M., Breidt, F.J., Fuller, W.A., 1998. Design and estimation for investigating the dynamics of natural resources. Ecological Applications 8, 234–245.

Paustian, K., Andren, O., Janzen, H.H., Lal, R., Smith, P., Tian, G., Tiessen, H., Van Noordwijk, M., Woomer, P.L., 1997a. Agricultural soils as a sink to mitigate CO_2 emissions. Soil Use and Management 13, 230–244.

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

Paustian, K., Cole, C.V., Sauerbeck, D., Sampson, N., 1998. CO_2 mitigation by agriculture: an overview. Climate Change 40, 135–162.

Paustian, K., Killian, K., Cipra, J., Elliott, E.T., Bluhm, G., Smith, J.L., 2001. Modeling and regional assessment of soil carbon: a case study of the conservation reserve program. In: Lal, R., McSweeney, K. (Eds.), Soil Carbon Sequestration and the Greenhouse Effect. Soil Science Society of America Special Publication Number 57, Madison, WI, pp. 207–225.

Pierce, F.J., Fortin, M.C., Staton, M.J., 1994. Periodic plowing effects on soil properties in a no-till farming system. Soil Science Society of America Journal 58, 1782–1787.

Reicosky, D.C., 1997. Tillage methods and carbon dioxide loss: fall versus spring tillage. In: Lal, R., Kimble, J.M., Follett, R.F., Stewart, B.A. (Eds.), Management of Carbon Sequestration in Soil. CRC Press, Boca Raton, FL, pp. 99–111.

Schertz, D.L., 1988. Conservation tillage: an analysis of acreage projections in the United States. Journal of Soil and Water Conservation 43, 256–258.

Six, J., Elliott, E.T., Paustian, K., 1999. Aggregate and soil organic matter dynamics under conventional and no-tillage systems. Soil Science Society of America Journal 63, 1350–1358.

Sobecki, T.M., Moffitt, D.L., Stone, J., Franks, C.D., Mendenhall, A.G., 2001. A broad-scale perspective on the extent, distribution, and characteristics of U.S. grazing lands. In: Follett, R.F., Kimble, J.M., Lal, R. (Eds.), The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. Lewis Publishers, Boca Raton, FL, pp. 21–63.

Stockfisch, N., Forstreuter, T., Ehlers, W., 1999. Ploughing effects on soil organic matter after twenty years of conservation tillage in Lower Saxony, Germany. Soil and Tillage Research 52, 91–101.

UNFCCC. 1997. Conference of the Parties, Decision 1/CP.3 Adoption of the Kyoto Protocol to the United Nations Framework Convention on Climate Change, 12th Plenary Meeting. 11 December 1997.

UNFCCC. 2000. United States Submission on Land-Use, Land-Use Change, and Forestry. In: United Nations Framework Convention on Climate Change, Subsidiary Body for Scientific and Technological Advice. Methodological Issues: Land-Use, Land-Use Change and Forestry, Submissions from Parties. FCCC/SBSTA/2000/MISC.6/Add. 1 September 2000.