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Estimating carbon sequestration potential on U.S. agricultural topsoils

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ABSTRACT

A better understanding of the potential for increasing soil carbon sequestration is necessary to estimate the greenhouse gas emission offset potential from agricultural soils. The objective of this research is to use the 2006 Intergovernmental Panel on Climate Change (IPCC) factors to estimate potential soil organic carbon (SOC) storage on U.S. agricultural land from widespread adoption of activities that are expected to increase SOC (e.g., remove highly erodible cropland from crop production, eliminate summer fallow, include winter cover crops in crop rotations, and widespread use of no-tillage). Previous land-use and management and the transitions between activities over three inventories are critical to the SOC estimates. The effects of these transitions between inventories are captured by using the ending SOC stock from the previous inventory for the SOC stock at the beginning of the next inventory. This approach increases the precision of SOC sequestration estimates based on the initial SOC stock, land-use and change in land-use, climate, soil characteristics, residue input, and soil disturbance. Total SOC storage during the final inventory is estimated to be 63.7 Tg C yr^{-1}, with over half (35 Tg C yr^{-1}) from new no-till management. The potential annual SOC accumulation could offset over half of the annual carbon dioxide (CO_2) emissions from U.S. agriculture in 2010 and all of the 1990–2010 average annual increase in U.S. CO_2 emissions. The approach provides more information than previous studies about the effect of land-use and tillage on SOC sequestration. No-till in the final inventory is estimated to accumulate 0.39 Mg C ha^{-1} yr^{-1} on cropland that was under reduced tillage the first inventory and conventional tillage the second inventory but 0.21 Mg C ha^{-1} yr^{-1} if the cropland was under reduced tillage the previous two inventories. This approach also captures the influence of soil characteristics on SOC sequestration. For example, land that was under continuous row crops prior to enrollment in the Conservation Reserve Program accumulated 0.39 Mg C ha^{-1} yr^{-1} on high activity mineral soils, but only 0.19 Mg C ha^{-1} yr^{-1} on sandy soils.

1. Introduction

Mechanisms to reduce or offset CO_2 emissions are of interest to countries concerned about the global impact of greenhouse gas (GHG) emissions. The 2010 Environmental Protection Agency (EPA) inventory estimated that U.S. CO_2 emissions increased by nearly 1% per year from 1990 to 2008, but decreased by an annual average rate of 1.2% per year between 2005 and 2010 (EPA, 2012). Emissions increased by 3.7% from 2009 to 2010 when they reached 1558 Tg C (5711 Tg CO_2 equivalent (Eq.); EPA, 2012), or more than 12% greater than 1990 emissions. Agriculture contributed approximately 116.8 Tg carbon (C) (428.4 Tg CO_2 Eq.) or 6.3% of total U.S. greenhouse gas emissions in 2010. Cropland, however, accumulated soil organic C (SOC), with mineral soils sequestering 11.8 Tg C (EPA, 2012). SOC accumulation in cropland is attributed to management systems that minimize soil disturbance, maximize crop residue retention, and production systems that maximize water and nutrient use efficiency (Paustian et al., 2000). Previous land management combined with site specific soil and climate characteristics must be accounted for when analyzing SOC changes (Liebig et al., 2005).

The Intergovernmental Panel on Climate Change (IPCC) developed a method to estimate SOC stock changes based on land-use and management that could be applied using land-use

Abbreviation: CT, conventional tillage; CTCTNT, conventional tillage, conventional tillage, no till; CTD, cold, temperate, dry; CTM, cold, temperate, moist; CTNTNT, conventional tillage, no till, no till; CTRTNT, conventional tillage, reduced tillage, no till; HAMS, high activity mineral soils (high clay concentration); IPCC, intergovernmental panel on climate change; LAMS, low activity mineral soils (low clay content); NT, no tillage; NTNTNT, no till, no till, no till; NTRTNT, no till, reduced tillage, no till; RT, reduced tillage; RTCTNT, reduced tillage, conventional tillage, no till; RTNTNT, reduced tillage, no till, no till; RTRTNT, reduced tillage, reduced tillage, no till; SOC, soil organic carbon; SRD, sub-tropical, dry; SRM, sub-tropical, moist; WTD, warm, temperate, dry; WTM, warm, temperate, moist.

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and management data that vary in detail (IPCC, 1997). The IPCC approach uses information about soil, climate, biomass input (crop intensity and permanence of biomass), and other attributes to estimate the change in SOC stock to a depth of 30 cm relative to the SOC stock under native vegetation (IPCC, 1997). The IPCC method applies fixed factors (base, input, and tillage) determined by land-use, land-use change, and soil disturbance (tillage) to estimate SOC stocks at the beginning and end of a twenty-year inventory. The IPCC (1997) method has been used to estimate SOC stocks on U.S. agricultural soils by Eve et al. (2001, 2002a,b) based on existing land-use and management and by Sperow et al. (2003) to estimate the potential for increasing SOC stocks from implementing activities that increase SOC sequestration.

The 1997 IPCC approach is limited to estimating total SOC sequestration rates by climatic region or management and overall average rates of change by crop rotation or land-use. Economic assessments and policy recommendations require SOC sequestration rates that suitably capture the spatial variability at a scale that provides information such as the sequestration potential on each hectare of common land-use based on previous land-use and management on that land unit. Sperow (2014) modified the 1997 IPCC approach to capture the change in SOC stocks by tracking the land-use and management changes on specific land units through time using the 1997 IPCC factors.

The IPCC (2006) updated the 1997 IPCC documentation to incorporate additional research to improve the coefficients used to estimate SOC changes. Table 1 presents the SOC stock under native vegetation provided by the 1997 and 2006 IPCC documentation, which differ for most combinations of soil and climatic regions. Hydric soils, except for dry climates, have SOC stocks that are an average of nearly 45% lower than they were in the 1997 IPCC documentation. The SOC stocks for sandy soils, conversely, are all nearly three times higher than estimated for the 1997 IPCC documentation.

The 2006 IPCC (chapter 5) replaced the 1997 IPCC base factor with a land-use factor (F_{LU}) to estimate the change the SOC stock under native vegetation that results when land-use changes from native vegetation. Tillage factors (F_{MG}) that account for land management are different from the factors presented in in the 1997 IPCC documentation. The effect of conventional tillage remains the same (F_{MG} = 1.0 in 1997 and 2006 IPCC guidelines), but the effect of reduced (F_{MG} = 1.0–1.05 in 1997 and 1.08–1.15 in 2006 IPCC guidelines) and no-till (F_{MG} = 1.1 in 1997 and 1.15–1.22 in 2006 IPCC guidelines) are higher than previously presented except for dry climatic regions, which are generally lower (F_{MG} = 1.02–1.10 in 2006 IPCC guidelines). The input factor (F_i), used to account for the effect of biomass residue on SOC sequestration, is somewhat higher for low (residue is removed or fallow is used; 0.9 in 1997 and 0.92–0.95 in the 2006 IPCC guidelines) and high residue input (high residue input such as green manure or cover crop; 1.1 in 1997 and 1.04–1.11 in 2006 IPCC guidelines), and the same for medium input (1.0 (chapter 5; IPCC, 2006)).

The land-use and management expected to provide the greatest increase in SOC on agricultural land are to remove highly erodible land (HEL) from crop production, include winter cover crops in rotations, eliminate bare summer fallow, and use no-till to minimize soil disturbance (Bruce et al., 1999; Cole et al., 1993; Lal et al., 1998, 1999; Paustian et al., 1997a,b).

Setting aside cropland provides the same SOC sequestration as cropland enrolled in the Conservation Reserve Program (CRP). The CRP was initiated in 1985 by the U.S. government as a voluntary program to retire environmentally-sensitive cropland for 10–15 years in return for annual payments. One early CRP objective was to reduce soil erosion by targeting cropland identified as HEL for enrollment in the program to plant native or introduced grass species or trees (USDA, 2004). Norton et al. (2012) estimated that CRP land could return SOC stocks to about 90% of the SOC stock that was present under native vegetation. Cropland enrolled in the CRP has been estimated to accumulate from 4.4 Tg C yr^{-1} (USDA, 2011) to 11 Tg C yr^{-1} with an upper estimate to 300 cm depth of 29 Tg C yr^{-1} (Gebhart et al., 1994). Because the CRP targeted HEL and provides substantial SOC increases, for this analysis, the HEL that was not already enrolled in CRP is removed from crop production to assess potential SOC accumulation from this activity.

In the cool and moist climatic regions, a grass or legume cover crop can be added to annual crop rotations after harvest to protect the soil over the winter by decreasing soil erosion, improving soil structure, and providing a green manure for the following season crop (Troeh et al., 1991). Winter cover crops also increase residue inputs to the soil which provides for increases in SOC sequestration (Campbell et al., 1991; Collins et al., 1992; Hu et al., 1997) especially when combined with conservation tillage (Hubbard et al., 2013).

Summer fallow, where soil remains bare between crops, is frequent in semi-arid regions of the U.S. to allow water to accumulate in the soil for use by the subsequent crop, most likely small grains. The concentration of SOC is generally lower in cropping systems that use summer fallow relative to continuous cropping (Bremer et al., 1994; Campbell et al., 2000; Campbell and Zentner, 1993; Janzen et al., 1998; Peterson et al., 1998; Sherrod et al., 2003, 2005). Cropping systems that include a crop instead of bare fallow, combined with no-till may reduce or eliminate the need for bare fallow (Peterson et al., 1998). No-till is analyzed because it often increases the concentration of stored SOC (Follett, 2001; Franzluebbers et al., 1998; Lal et al., 1998; Ogle et al., 2005; Paustian et al., 1997a; Six et al., 1999; West and Post, 2002).

The objective of the research presented here is to estimate potential SOC increases in mineral soils that may be attained by setting aside HEL, use of winter cover crops in the crop rotation, no

Table 1
Comparison of soil carbon content under native vegetation values (reference soil C; SOC^R) provided by the 1997 and 2006 IPCC documentation.

Climatic region[a]	Soil[b]									
	HACS		LACS		Sandy		Volcanic		Hydric	
	1997	2006	1997	2006	1997	2006	1997	2006	1997	2006
	Soil carbon stock (Mg C ha^{-1})									
CTD	50	50	40	33	10	34	20	20	70	87
CTM	80	95	80	85	20	71	70	130	180	87
STD	60	38	40	35	4	31	50	50	60	86
STM	140	65	60	47	7	39	100	70	140	86
WTD	70	38	60	24	15	19	70	70	120	88
WTM	110	88	70	63	25	34	130	80	230	88

[a] CTD, cool temperate dry; CTM, cool temperate moist; STD, subtropical dry; STM, subtropical moist; WTD, warm temperate dry; WTM, warm temperate moist.
[b] HACS, high activity clay soils (lightly to moderately weathered mineral soils dominated by 2:1 silicate clay minerals); LACS, low activity clay soils (highly weathered soils); hydric (soils with restricted drainage with periodic flooding).Source: IPCC (2006).