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An enhanced method for using the IPCC approach to estimate soil organic carbon storage potential on U.S. agricultural soils

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ABSTRACT

The Intergovernmental Panel on Climate Change (IPCC) provides a method to estimate soil organic carbon (SOC) stock changes relative to the SOC stock under native vegetation. This manuscript modifies the IPCC approach to use the ending SOC stock from the previous inventory as the SOC stock that is changed by land use and management activities during the next inventory and to track the crop rotation and tillage intensity through three inventories. The approach allows annual rates of change of carbon sequestration from different historic land uses and management to be estimated explicitly for each assessment point based on the effect of previous land use and management. The model generates 3524 unique annual SOC sequestration rates that vary by land use and management history on U.S. agricultural land based on the 30 SOC stock reference values provided by IPCC documentation. An average of 0.33 Mg C ha^{-1} yr^{-1} is stored when cropland that was conventionally tilled in two previous inventories is set-aside in the third inventory, but only 0.14 Mg C ha^{-1} yr^{-1} when it is conventionally tilled in the first inventory and no-till in the second inventory before it is set aside. Incorporating a winter cover on cropland that was conventionally tilled in the first inventory and no-till in the second and third inventories is estimated to store 0.49 Mg C ha^{-1} yr^{-1}, but could store 0.81 Mg C ha^{-1} yr^{-1} if it was conventionally tilled in the first two inventories and under no-till in the final inventory. Cropland under conventional tillage in the first two inventories and no-till the final inventory could store an average of 0.34 Mg C ha^{-1} yr^{-1}, but cropland under conventional tillage in the first, reduced tillage in the second, and no-till in the third inventory is estimated to store 0.19 Mg C ha^{-1} yr^{-1}. The detailed annual rates of SOC stock change estimated using the approach is useful for economic or other analyses and for policymakers.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) method was developed to estimate the change in soil organic carbon (SOC) stock over two time periods relative to the SOC stock under native vegetation (IPCC, 1997a). It uses fixed factors (base, input, and tillage) to account for SOC stock changes from land-use or management (e.g., soil disturbance and residue input) between the first and last year of a 20-year inventory period to a depth of 30 cm. The SOC stock estimates are dependent upon soil characteristics, climate, biomass input (crop intensity and permanence of biomass), and other inputs to the production process. The IPCC method has been applied to assess SOC storage in the U.S. (Eve et al., 2001, 2002) and to project SOC storage from future land use and management in the U.S. (Sperow et al., 2003), the Brazilian Amazon (Cerri et al., 2007), and Kenya (Kamoni et al., 2007).

Eve et al. (2001, 2002) used the IPCC method to estimate the change in SOC stocks from land use and management changes on U.S. agricultural soils between 1982 and 1997. Sperow et al. (2003) used the IPCC method to estimate the potential for increasing SOC stocks on U.S. agricultural soils by implementing activities that enhance SOC storage. They first estimated the SOC stock on agricultural land using the base, tillage, and input factors appropriate for the land-use and crop management activities in 1982. Then, the base, tillage, and input factors appropriate for the land-use and management activities in 1997 were used to estimate the SOC stock in 1997. The SOC stock change was estimated by subtracting the 1982 estimate from the 1997 estimate and the results indicate how the reference SOC stock changed under different land use or management in 1997. Then they projected the change in SOC stock relative to the reference SOC stock by comparing the 1997 estimate to the SOC stock that could occur if land-use and crop management activities that enhance SOC storage had been implemented in 1997.

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Following the IPCC method, Eve et al. (2001, 2002) and Sperow et al. (2003) estimated SOC stock changes between 1982 and 1997 by comparing the 1997 estimates to the SOC stock estimated for land use and management activities in 1982. The same reference SOC stock was used for each inventory, adjusted by the base factor, which accounts for the change in SOC stocks when the land is changed from native vegetation to another use. These approaches using the IPCC provide estimates of total changes in SOC stocks and overall average annual rates of change, but do not account for the effect of specific land use and management changes through different inventory periods that would allow for more extensive use of the data.

The analysis presented here uses a modified IPCC inventory approach to estimate SOC stock changes on U.S. agricultural land with the assumption that the land-use and crop management activities present at the beginning of each inventory period remain the same for the duration of the inventory period. This analysis uses the same data as Sperow et al. (2003) to identify crop rotations, soil characteristics, and other factors to estimate the SOC stock in 1982 and the change in stock between 1982 and 1997 based on the land-use and crop management activities. Then, the SOC stock at the end of the inventory is used as the beginning SOC stock for analyzing the change in SOC stock when the land-use and crop management activities in 1997 are implemented. The potential for increased SOC storage on U.S. agricultural soils is estimated by adopting activities that enhance SOC storage following the 1997 inventory and projecting these changes for the twenty year inventory period. Unlike the IPCC analysis presented in Eve et al. (2001) and Sperow et al. (2003), the current analysis estimates the change in SOC between inventory periods based on the crop rotation and management activities that are traced throughout all three inventory periods.

The purpose of this manuscript is to document the updated approach to using the IPCC data and compare the results to the approach implemented by Sperow et al. (2003) to estimate potential changes in SOC stocks from activities that enhance SOC storage. To allow for a direct comparison to previous research that used the IPCC method, this research uses the same coefficients and data to estimate changes in SOC storage rates and for identifying land use and land use changes. The updated approach using the IPCC method is presented first, and then general results are presented with a comparison to previous analyses using the IPCC method, and finally a discussion of the model attributes that demonstrate improvements is presented.

2. Data and methods

The management activities that are expected to increase SOC storage on agricultural land are to convert highly erodible land (HEL) to set-aside, incorporate winter cover crops, eliminate summer fallow operations, and adopt low soil disturbance tillage (Cole et al., 1993; Lal et al., 1998, 1999; Bruce et al., 1999; Paustian et al., 1997a,b). Land use and management changes that enhance SOC storage are sequentially analyzed to avoid double-counting non-complementary SOC sequestration activities. Cropland placed into set-aside could not also benefit from reduced tillage intensity or fallow elimination, thus these are non-complementary activities. Winter cover crops and decreased tillage intensity are complementary activities because implementation of one activity does not preclude and may enhance the other activity. To ensure SOC accumulation or losses are not double-counted, the SOC sequestration potential is analyzed by incorporating activities into the model in the order of set-aside HEL, include winter cover crops, reduce bare fallow, and finally, reduce tillage intensity. Winter cover crops are included only in regions with a climate necessary for successful implementation (e.g., moist climatic regions) and they are not included in crop rotations that already included hay.

2.1. IPCC inventory approach – overview

The IPCC method uses SOC stocks under native vegetation (i.e. uncultivated) as a reference for estimating SOC changes associated with land use and/or management change between the beginning and end of the inventory period. Land use and management effects on the reference SOC stock are captured by a base factor (*BF*) to account for long term land use (range from 0.5 to 1.1), tillage factor (*TF*) for the effect of soil disturbance (range from 0.8 for CT to 1.1 for NT), and the input factor (*IF*) to estimate the effects of carbon inputs from biomass residue (range from 0.8 to 1.1). The fixed factors provided for the IPCC method generate a constant annual rate of change for the SOC stock over the length of the inventory period.

The reference SOC stock varies by climate and soil characteristics with default values based upon global soils information derived from FAO and USDA soils information, compiled by the World Soils Resources division of USDA-NRCS (Eswaran et al., 1993). The *BF*, *TF*, and *IF* also vary by climate. Six climatic regions are delineated for the conterminous U.S. (Fig. 1) based on IPCC criteria: cold temperate dry (CTD); cold temperate moist (CTM); warm temperate dry (WTD); warm temperate moist (WTM); sub-tropical moist (STM); and sub-tropical dry (STD) (Eve et al., 2001). The land use activities (crop rotations, area under forest, urban, cropland, etc.) used to estimate SOC changes were derived from the 1997 National Resources Inventory (NRI) data. The NRI is a dataset with over 1.3 million actual and imputed locations that identifies land use, land characteristics, crops, and other information that has been collected every five years since 1982 (Nusser and Goebel, 1997). For this paper, the change in SOC is estimated for each observed and imputed NRI point, each of which has statistically determined area expansion factors (Nusser and Goebel, 1997), to derive estimates of SOC stock change for all cropland in the conterminous U.S.

The IPCC (1997a) identifies five soil types based on characteristics such as texture, mineralogy, and drainage because these characteristics influence the ability to stabilize SOC and to account for management responses. The dominant taxonomic soil order and associated NRI points within the model were established by Eve et al. (2001) by referencing the soil map unit identifier, which is linked to each NRI point (NRCS, 1994). Each NRI point was classified by climate and soil type with the state, county, and Major Land Resource Area (MLRA) membership used to locate the point within a climate region (Sperow et al., 2003). Each MLRA represents an area with similar soils, climate, water resources, and land uses as defined by the USDA-NRCS (NRCS, 1981).

The percentage of cropland under different tillage intensities (no-tillage (NT), reduced tillage (RT), or conventional tillage (CT)) is used to allocate area of cropland by tillage intensity for the analysis. Long term (five consecutive years) NT practice with adequate moisture is required for NT cropping systems to increase SOC relative to CT (Six et al., 2004; Abreu et al., 2011). Data were provided by the Conservation Tillage Information Center (CTIC) that address longer term (greater than 5 years) adoption of reduced tillage by IPCC climatic region and crop rotation (Eve et al., 2001). The CTIC data indicate that, while tillage intensity varies by cropland and climatic region, 1–12% of U.S. cropland was under NT in 1997, which is similar to more recent studies that estimated longer term (over 3 year) NT adoption on 13% of the 4.9 Mha (million hectares) of the cropland evaluated (Horowitz et al., 2010).

2.2. Adjustments to IPCC inventory method

The SOC stock change depends on the land use, management, soil characteristics, and climate in the current inventory, as well