Estimating Regional Changes in Soil Carbon with High Spatial Resolution

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To manage lands locally for C sequestration and for emissions reductions, it is useful to have a system that can monitor and predict changes in soil C and greenhouse gas emissions with high spatial resolution. We are developing a C accounting framework that can estimate C dynamics and net emissions associated with changes in land management. One component of this framework integrates field measurements, inventory data, and remote sensing products to estimate changes in soil C and to estimate where these changes are likely to occur at a subcounty (30- by 30-m) resolution. We applied this framework component to a midwestern region of the United States that consists of 679 counties approximately centered around Iowa. We estimated the 1990 baseline soil C to a maximum depth of 3 m for this region to be 4117 Tg. Cumulative soil C accumulation of 70.3 Tg was estimated for this region between 1991 and 2000, of which 33.8 Tg is due to changes in tillage intensity. Without accounting for soil C loss following changes to more intensive tillage practices, our estimate increases to 45.0 Tg C. This difference indicates that on-site permanence of soil C associated with a change to less intensive tillage practices is approximately 75% if no additional economic incentives are provided for soil C sequestration practices. This C accounting framework offers a method to integrate inventory and remote sensing data on an annual basis and to transparently account for alternating annual trends in land management and associated C stocks and fluxes.

Abbreviations: CDL, Cropland Data Layer; CRP, Conservation Reserve Program; CTIC, Conservation Technology Information Center; FIPS, Federal Information Program Service; MCI, Mid-Continental Intensive; MODIS, Moderate-Resolution Imaging Spectroradiometer; NASS, National Agricultural Statistics Service; NLCD, National Land Cover Data; STATSGO, State Soil Geographic database.

Efforts are being made to reconcile bottom-up (land-based) and top-down (atmosphere-based) estimates of C fluxes between the biosphere and atmosphere (see Denning, 2004). One such initiative is focused on a predominantly agricultural region in the midwestern United States (Ogle et al., 2006). Estimates of soil C flux within this region are being used in comparisons, and in conjunction, with estimates derived from eddy covariance flux towers to improve estimates and reduce uncertainty of the total regional C budget (Ogle et al., 2006).

A number of data sources are needed to measure, model, and predict changes in soil C flux (Izaurralde, 2005). To obtain soil C flux estimates with high spatial resolution and that cover a large geographic region, data are particularly needed that (i) represent local- to field-scale C dynamics, (ii) are consistently collected across the region of interest, and (iii) enable the attribution and distribution of C dynamics to appropriate land use classes across the region. Data that meet these requirements are, respectively, in situ field measurements, national inventory data, and remote sensing products.

In this study, we developed a method for integrating field, inventory, and remote sensing data to develop estimates of changes in soil C as a function of crop rotation, tillage intensity, land management, and initial soil C content. This method was developed for a soil C accounting component that is part of a larger C accounting framework that includes a greenhouse gas emissions component and an agricultural economics component. The complete framework is being developed to predict changes in land use, farm profit, and net C-equivalent emissions. A primary goal of the soil C modeling component presented here, and of the larger C accounting framework, is to

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use high-resolution remote sensing data to enhance the representation of soil spatial heterogeneity and to estimate the sub-county location of soil C change and net C-equivalent fluxes.

While the integration of available data at different scales is not new, there are efforts currently underway to integrate data in a more robust manner and to use the final products to address a number of current issues, including land use change, C dynamics, and climate change (Melton et al., 2005). Potter et al. (2006), for example, used Advanced Very High Resolution Radiometer (AVHRR) and Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite data with modeled predictions of soil CO_2 flux to estimate net ecosystem production for U.S. ecosystems. They used the AVHRR and MODIS data to estimate net primary production and to spatially delineate land cover classes, respectively.

Hurtt et al. (2001) provided a similar example of data integration. They indicated that census or inventory data are useful sources for information on land use, but that these data are commonly defined for political domains and are too coarse for analyses of ecosystem dynamics. On the other hand, remote sensing data have the needed spatial resolution but often lack information on land use. To address this issue, Hurtt et al. (2001) linked a 1-km-resolution, AVHRR-based land cover data set to U.S. state-level census data on land uses. The product is essentially a fusion of 16 land cover classes from the AVHRR data set with four land cover classes from the census data. Such products will continue to prove useful as data input to ecosystem and C cycle models.

Regional estimates of C flux from soils can be developed with a process-based approach using biogeochemical modeling or with a statistical approach that relies more on aggregated field measurements associated with land management and environmental variables. The two approaches often complement each other in that the statistical approach, being less complex and more transparent, can be used to confirm results from the process-based approach, while a process-based approach aids in understanding the cause of changes in C stocks and fluxes and the feedbacks among environmental variables. We used a statistical approach in this study to facilitate the development of our data integration method and for the purpose of transparent C accounting. A process-based biogeochemical model can also be substituted for the statistical, field-based estimates of soil C change in our framework.

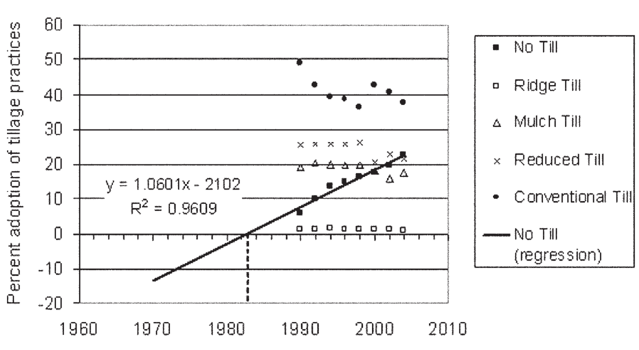

Fig. 1. Historical adoption of tillage practices in the United States. Data are from the Conservation Technology Information Center (2004).

Our method differs from, and extends, other efforts by integrating unique data sets at a higher resolution and by using the newly integrated data sets to estimate the location of net soil C fluxes due to annual changes in land management. Our analysis was based on a region in the midwestern United States that consists of 679 counties in 11 states that are approximately centered around the state of Iowa. This region coincides with the Mid-Continent Intensive (MCI) experiment of the North American Carbon Program (Ogle et al., 2006).

MATERIALS AND METHODS

We developed a method to integrate field, inventory, and remote sensing data to estimate soil C flux at a high spatial resolution. This method used Landsat-based remote sensing products, three U.S. national inventory data sets, and a compilation of data from hundreds of field experiments. These data sources, and the integration among them, are discussed below.

Inventory Data—Cropland Area And Tillage Practices

Data from the National Agricultural Statistics Service (2006) provided annual estimates of crop area per county for each major crop type. Data from the Conservation Technology Information Center (2004) provided information on the area of major crop types using different tillage practices, including conventional tillage, reduced tillage, and conservation tillage. These three tillage practices are defined, respectively, as leaving <15% of the ground covered by crop residue, between 15 and 30% ground cover, and >30% ground cover (Conservation Technology Information Center, 2004). Conservation tillage encompasses tillage practices such as mulch till, ridge till, and no-till. For our analysis, we aggregated mulch till and ridge till with the reduced tillage category, and we maintained no-till and conventional tillage as separate categories. This revised classification coincides with previous statistical analyses of field data (West and Post, 2002; West and Six, 2007).

While the Conservation Technology Information Center (CTIC) data provided information on the area under crop and tillage type, we used the National Agricultural Statistics Service (NASS) annual survey data as the definitive source for crop area. The NASS data layer provided estimates of crop area per county, to which the percentage of tillage intensity per crop from the CTIC data was applied. Exceptions to this method include fallow cropland area, taken directly from the CTIC data, and land under the Conservation Reserve Program (CRP), obtained from the USDA Farm Service Agency (Farm Service Agency, 2006). In cases where the NASS land area for a given crop and county had no associated CTIC tillage data, the NASS land area was divided into tillage management categories based on state-level ratios for the respective crop.

The CTIC data are provided annually from 1989 to 1998, and biannually from 1998 to 2004. Tillage data for odd years after 1998 were estimated as an average between the prior and following years. Since CTIC tillage data collection began in 1989, an estimate was needed of when reduced tillage and no-till practices were initially adopted. Plotting biannual tillage data for the United States suggested that no-till practices are more recent than other conservation tillage practices, including ridge till and mulch till. As a first approximation, we used a simple linear regression to extrapolate the rate of adoption of no-till in the United States, and we estimated that initial adoption of no-till began in 1983 (Fig. 1). With respect to soil C in our analysis, this means that some lands using no-till had been accumulating soil C for 7 yr before the 1990 baseline. Figure 1 illustrates an inverse relationship between conventional tillage and no-till from 1989 to 1996, indicating that much of the no-till land area was adopted on lands using conventional tillage. Although we used a linear regression to estimate large-scale adoption of no-till beginning in the early 1980s, we recognize that adoption of new agricultural technology commonly follows a nonlinear, sigmoidal function (Griliches, 1957) and that a small percentage of U.S. agricultural lands have been using no-till practices since the early 1960s (Derpsch, 2004).

Adoption rates for reduced tillage, mulch till, and ridge till were steady between 1989 and 1996, unlike adoption rates for no-till. As such, we assumed that lands in reduced till, mulch till, and ridge till up to 1990 were in steady state and had already accumulated C for the maximum 20-yr accumulation period (West and Post, 2002; West et al., 2004). Data for CRP lands are available from the program inception (1985) to present. Soil C accumulation under CRP was estimated on an annual basis before and after the 1990 baseline.

In our C accounting framework, crop rotations were not explicitly considered; however, C accumulation rates used in our framework differed among crops and tillage types. Therefore, changes in annual crop and tillage inventory data change soil C accumulation and loss rates accordingly, thereby simulating crop rotations and annual changes in tillage intensity. Our framework focused on the management of croplands, and did not explicitly consider changes in land cover (i.e., conversion from cropland to forest).

Inventory Data—Soils

The State Soil Geographic (STATSGO) database, Version 1.0 (Soil Survey Staff, 1994a), was used to obtain initial information for soil attributes. Data included in STATSGO represent a generalization of the Soil Survey Geographic (SSURGO) data for the United States (Soil Survey Staff,1994b). Soil characterization data from the National Cooperative Soil Survey were collected in support of preparing SSURGO, and these data were used to formulate various landscape models that were then used to develop detailed soil survey maps and estimates of soil physical and chemical properties (Sharon Waltman, USDA, personal communication, 2006). Soil properties in the characterization data and in SSURGO were aggregated for use in STATSGO to represent approximately 18,000 recognized soil series in the United States (Soil Survey Staff, 1994a).

In preparation for the release of STATSGO in 1994, incorporation of new soils data into STATSGO ceased in late 1993. Of 4595 complete soil surveys for the contiguous United States, 664 or 14% are from the period 1983 to 1993. Similarly, 15% of the soil survey data for states included in the MCI region are from this time period. Therefore, approximately 85% of soil series data used in the development of STATSGO were taken before 1983 (i.e., before no-till practices became more widely adopted). In our analysis, we assumed that the soil C content derived from STATSGO soil attributes represented a steady-state level of soil C following decades of conventional tillage. In a previous analysis of tillage and soil C content, Kern and Johnson (1993) estimated changes in soil C for each Major Land Resource Area using soils data from the 1982 Natural Resource Inventory. Kern and Johnson (1993) similarly assumed that soil C was near a steady state, but estimated that soils would lose another 10% of their initial soil C under continued conventional tillage during the initial 30 yr of their model simulation.

The STATSGO-delineated soil map units encompass between 1 and 26 soil components, representing phases of soil series. Soil series phases represent environmental distinctions within soil series that are relevant to land management, such as slope position and slope steepness (Soil Survey Division Staff, 1993). Each soil series phase within a map unit has been given a high and low value for each soil attribute (e.g., soil organic matter, bulk density, soil layer depth, soil texture, etc.). To generate a baseline soils map, we averaged the high and low values for attributes of each soil series phase, converted soil organic matter content to soil organic C content, multiplied the C content by soil bulk density and by the depth of the respective soil layer, and corrected for the percentage of rock fragments in each soil layer. Soil C was estimated by 20-cm intervals to a 1-m depth and then by 1-m intervals from the 1- to 3-m depth, according to vertical soil C distributions based on 1271 cropland soil samples analyzed by Jobbágy and Jackson (2000). The depth of the soil profile was based on depth-to-bedrock estimates provided in STATSGO. A weighted average of soil C was calculated among soil series phases within each soil map unit, resulting in one soil C estimate for each spatially delineated soil map unit. Soil C estimates were then revised to reflect accumulations and losses of soil C resulting from changes in crop management up to 1990, based on county crop and tillage practices in the NASS and CTIC data. The methods used to estimate changes in soil C are discussed below.

The Soil Survey Staff (1994a) cautioned that STATSGO data are not detailed enough to make interpretations at the county level. We did, in fact, use these data to interpret C flux at the subcounty level. We emphasize that we are presenting a framework for the integration of multiple data sources and that more detailed data (i.e., SSURGO) can be inserted when wall-to-wall continental coverage is available, or a more detailed framework can be implemented currently for smaller regional areas. Additionally, STATSGO data were advantageous for use in our framework because of the spatially delineated map unit boundaries. While it was not our intent to estimate the exact amount of soil C on a specific plot of land, we are confident that (i) the amounts of soil C estimated adequately reflect regional trends in U.S. soil C, and (ii) relative changes in soil C can be reasonably captured at the subcounty level. Bliss et al. (1995) provided additional details on the origin of, and the differences between, STATSGO and SSURGO; the use of STATSGO for estimating soil C; and the importance of spatial soil C estimates for balancing regional and global C budgets.

Remote Sensing

Inventory data available at the county scale (i.e., CTIC and NASS) are organized by Federal Information Program Service (FIPS) codes. We distributed these data spatially based on land cover classes from remote sensing products and then combined the result with respective soil attributes and land management practices to estimate changes in soil C. The spatial distribution of the estimated values of soil C flux depends on the land use classification used in the remote sensing product. The remote sensing product used in this analysis is the National Land Cover Data (NLCD), based on cloud-free LandsatTM imagery collected between 1991 and 1992 (Vogelmann et al., 2001).

Any remote sensing product that provides data on agricultural land use can be used in this framework. Spatial estimates of soil C flux will probably become more spatially accurate as the delineation of crop types increases (i.e., more crop categories or classes) in the remote sensing products. For example, the Cropland Data Layer (CDL) is a classification of LandsatTM and LandsatETM+ remote sensing data and it is completed in conjunction with the NASS June Agricultural Survey (National Agricultural Statistics Service, 2005). Each crop in the NASS survey is represented in the remote sensing classification. With this data set we would know, for example, where

Table 1. Estimated soil C accumulation following a decrease in tillage intensity.†

Land use	Carbon accumulation following reduction in tillage intensity	
	CT to NT‡	CT to RT or RT to NT‡
	% of initial soil C	
Corn and soybean	20.7 ± 6.3	10.4
Other§	6.4 ± 9.5	3.2
Wheat and small grains	18.6 ± 6.9	9.3
Pasture or forage	36.9 ± 88.3	18.5
Fallow	6.3 ± 4.8	3.2
Set-aside (CRP)¶	62.7 ± 20.4#	–

† Sources: West and Post (2002), West et al. (2004), and Conant et al. (2001).This is the total C change following the change in tillage practice. Change was estimated to occur as 20 equal annual increments during a period of 20 yr.

‡ CT, RT, and NT are conventional tillage, reduced tillage, and no-till, respectively.

§ Includes sorghum, cotton, and other crops not listed.

¶ The value given for set-aside lands represents lands enrolled in the Conservation Reserve Program (CRP). The C accumulation value represents soil C accumulation following a change from cultivated land to perennial pasture; it does not reflect a change in tillage occurring on set-aside lands.

sorghum [*Sorghum bicolor* (L.) Moench], cotton (*Gossypium hirsutum* L.), and corn (*Zea mays* L.) are located on the land surface, instead of having these crops aggregated into a single category representing row crops (as is done in the NLCD). The CDL coverage, however, is not currently available for the entire MCI region.

In our analysis, we used the NLCD as the temporal reference point for the spatial delineation of soil C fluxes. New remote sensing products that provide data on changes in land cover can be integrated into this framework on an annual basis. For example, the NLCD 2001 coverage (Homer et al., 2004) can be inserted into the framework for the respective year of analysis. Annual remote sensing products like the CDL or MODIS products can be inserted for each respective year of the analysis, similar to the annual NASS and CTIC data (biannual after 1998).

Field Measurements—Soil Carbon Accumulation

Field measurements are taken to meet the specific objectives of individual field experiments. These objectives may or may not be consistent with the needs of a regional or continental analysis. To use field measurements for the purposes of large-scale modeling or C accounting efforts, these measurements need to be compiled, standardized to similar dimensional units, and analyzed according to similar cropping practices and environmental variables. Compilation and analysis of cropland field data, with respect to tillage and other C sequestration strategies, has been completed by Ogle et al. (2003, 2005), Smith et al. (1998), VandenBygaart et al. (2003), and West and Post (2002). Additional analyses on the effects of land use change on soil C dynamics have been summarized and discussed by West et al. (2004).

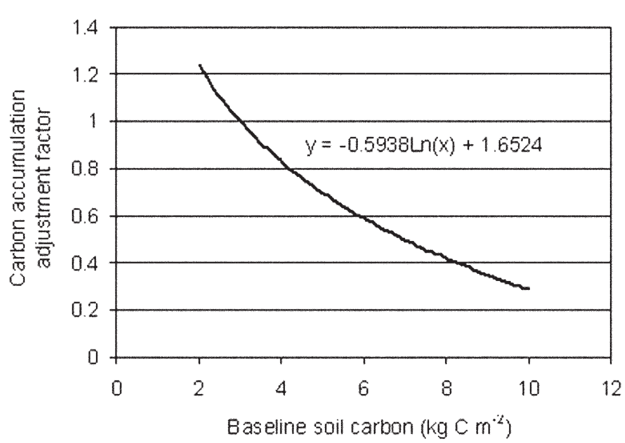

Fig. 2. Adjustment factor for C accumulation rates (Table 1) as a function of initial or baseline soil C. Analysis based on data compiled by Tan et al. (2006).

In our framework, annual changes in cropland area and tillage practices, derived from the NASS and CTIC data, were accompanied by changes in soil C based on data from field experiments compiled by West and Post (2002) (Table 1). The total expected accumulation of soil C following decreases in tillage intensity was assumed to occur linearly during a 20-yr period (West and Post 2002; West et al., 2004). Carbon accumulation rates were initially estimated as a percentage or fraction of the initial soil C. The fraction was adjusted as a function of the baseline soil C (Fig. 2) and then multiplied by the baseline soil C content associated with respective cropping practices. Adjusting the rate of soil C accumulation was based on an analysis by Tan et al. (2006) that indicates increased sequestration rates with lower baseline soil C and reduced sequestration rates with higher baseline soil C. Accumulation rates for a change from conventional tillage to reduced tillage, or from reduced tillage to no-till, were assumed to be half of that associated with a change from conventional tillage to no-till (see Table 1). While this stepwise change in soil C associated with the successive tillage intensities is not necessarily supported by analyses of field data (West and Post 2002), we used this method to simplify accounting as land areas move in a stepwise progression from conventional tillage to reduced tillage and then to no-till. The end result of this stepwise scenario, in terms of soil C, is thus the same as a direct change from conventional tillage to no-till.

Ogle et al. (2005) similarly estimated soil C accumulation for a change in tillage intensity by analyzing data from field experiments. Their approach differs in that their factor for C accumulation is the product of two separate factors: a factor representing changes in soil C associated with different tillage practices and a factor representing changes in soil C associated with different quantities of residue input. In the approach we used here, differences in residue input were, to a large extent, captured when estimating soil C change for different crops or crop rotations.

In an early effort to estimate changes in soil C caused by the adoption of conservation tillage practices, Kern and Johnson (1993) reversed a linear regression equation for soil loss from cultivation (based on Mann, 1986) to estimate soil C gain when moving to no-till. Initial soil C values were based on 1982 Natural Resource Inventory soil samples extrapolated to the Major Land Resource Areas. A county-level resolution was used since there were no remote sensing data utilized in the analysis.

For CRP lands, we assumed that lands were converted from cultivated cropland to grassland. Data compiled by Conant et al. (2001), consisting of data on 51 paired plots, indicate a 65.9 ± 20.9% increase in soil C during a mean experimental duration of 23 yr. Based on analyses by Conant et al. (2001), West et al. (2004), and West and Post (2002), we anticipated that C accumulation will occur for about 40 yr following changes in residue inputs. Using a C management response curve for accumulation on lands converted to grassland (West et al., 2004), we estimated an approximate 70% increase in soil C over 40 yr. Gebhart et al. (1994) reported a mean 18.8% increase on five CRP sites during a 6-yr period, which would yield a 78% increase if continued for a 40-yr period. Since our framework is based on accumulation over 20 yr, we used data from Conant et al. (2001) to estimate a 62.7 ± 20.4% increase over 20 yr, or 3.13% per year. This rate of accumulation is adjusted in our framework as a function of baseline soil C (Fig. 3) according to analyses by Tan et al. (2006).

Field Measurements—Soil Carbon Loss

In our framework, soil C was reduced if tillage intensity was increased (e.g., a change from no-till to reduced tillage or to conventional tillage). The amount of soil C lost following tillage of soils previously under no-till management is not well known or well documented at this time. Recent studies that measured soil C following a one-time tillage event vary greatly in their estimates of soil C loss (Table 2). As a first approximation, for an intermittent increase in tillage intensity we estimated an annual loss of soil C equivalent to the annual gain in soil C for the respective crop and tillage practices. This approach allows for a linear decline in soil C associated with a change to more intensive tillage practices, and it allows for less C loss if land under no-till goes to reduced tillage than if it goes to conventional plow tillage. If the land area under no-till continues to decline, soil C will be reduced each subsequent year in proportion to the changing land area.

While others have indicated that C loss following an increase in tillage intensity will occur over several years (e.g., Davidson and Ackerman, 1993), this represents soil C loss following multiple years of C accumulation and its distribution to both labile and stable soil C pools. It is well established that soil C accumulation occurs over a longer time period than soil C loss (West et al., 2004). If soil C accumulates in 1 yr due to a change to no-till, however, it is unlikely that this 1-yr accumulation would take 3 to 5 yr to oxidize following a change to conventional tillage. Within our C accounting framework, we are trying to capture short-term (annual) alternations between soil C accumulation and loss. Our first approximation that the rate of soil C loss equals the rate of soil C accumulation allows for soil C accumulation with intermittent tillage while still representing soil C losses due to intermittent changes from no-till to reduced or conventional plow tillage. Additional research is needed to estimate C flux in the first year following a one-time tillage event, and to estimate the impact of a one-time tillage event on longer term trends in soil C accumulation.

Unlike our treatment of changes in tillage practice, we did not subtract soil C in our framework if there was less CRP land area in 1 yr vs. the previous year. Available data do not permit us to know the fate of land taken out of the CRP. Additionally, if land under CRP is returned to cultivation, some or all of the soil C can potentially be retained if the land is cultivated with no-till practices (Bowman and Anderson, 2002; Dao et al., 2002; Olson et al., 2005).

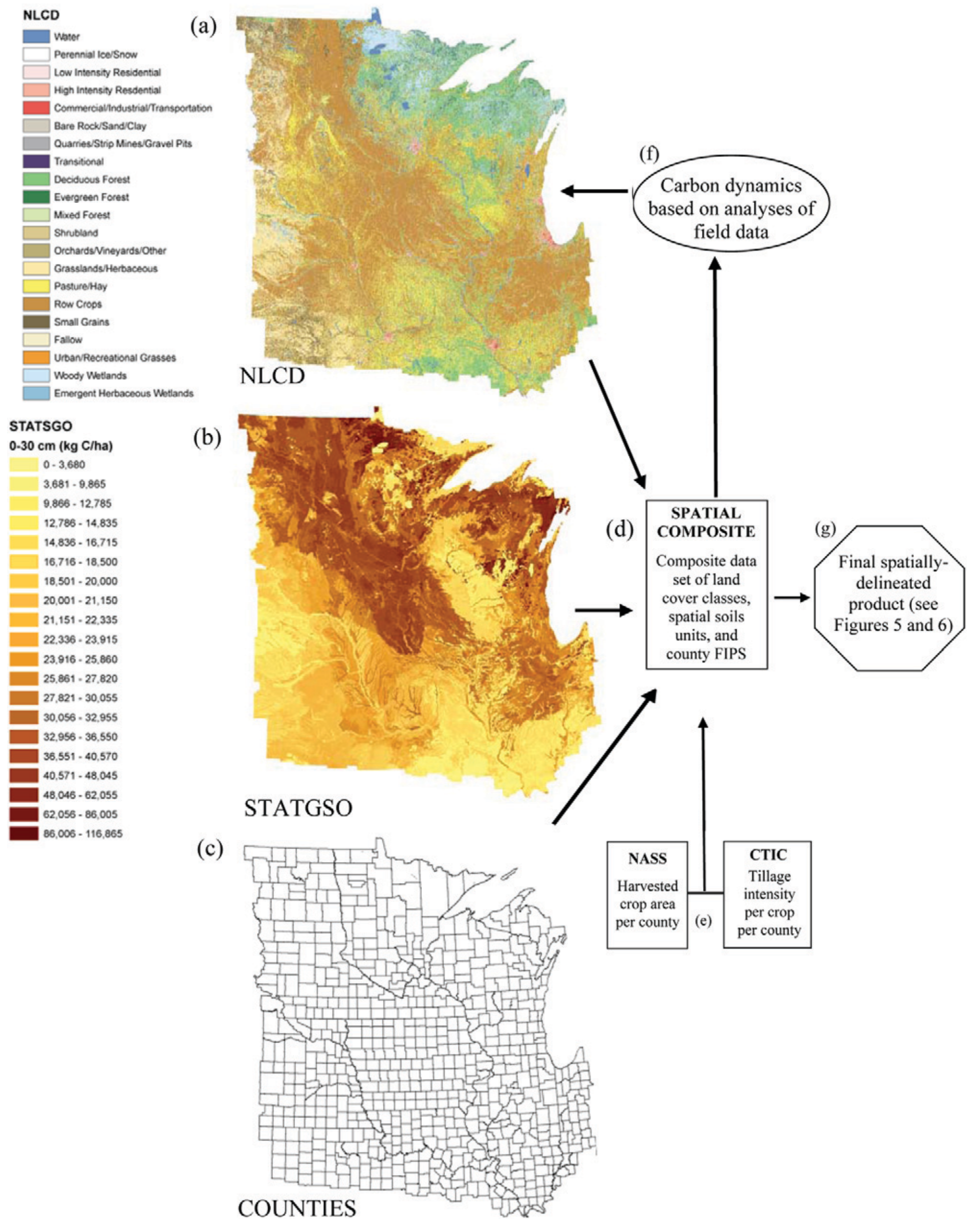

Fig. 3. Integration of field, inventory, and remote sensing data used in the development of this C accounting framework. The (a) National Land Cover Data (NLCD) land use classes, (b) State Soil Geographic database (STATSGO) map units, and (c) county Federal Information Program Service values were integrated into (d) one composite layer that summarizes the unique combinations of the three values. Annual adoption rates (e) of different tillage intensities (from Conservation Technology Information Center [CTIC] data) were applied to the area of respective crop types (from National Agricultural Statistics Service [NASS] data). The new data set was combined with C dynamics derived from field experiments (f) using initial soil C values (b) to estimate changes in soil C that were then distributed across areas of respective cropland classes in the NLCD (a). A final spatial data set (g) of estimated C flux was generated.

Table 2. Estimated loss in soil C following a one-time tillage event on land previously in no-till.

Reference and experiment plot	Location	Time in no-till	Time measured after tillage	Change in total soil C	Change relative to previously sequestered C
		—— yr ——		—— % ——	
VandenBygaart and Kay (2004)	Ontario, Canada	22	1.5		
Sandy loam (high clay)				0	0
Sandy loam (low clay)				−10	−66
Sandy clay loam				0	0
Silty clay loam				0	0
Pierce et al. (1994)	East Lansing, MI	6	~5		
1986 plot				3.7	–
1987 plot				−2	−16
Kettler et al. (2000)	Sidney, NE	20	5	0	0
Stockfisch et al. (1999)	Saxony, Germany	20	2	−10	−142
Average		17.5	2.9	−2.3	−28.0

Integration of Data Sets

The data sets described above were integrated within our framework to identify specific combinations of crop, tillage, soil, and management practices, and to spatially estimate where these particular combinations occur across the landscape. There are differences in the spatial resolution among the data sets used (Table 3). It is important to recognize that the final 30-m-resolution product, coinciding with the NLCD land classification, does not demonstrate that a specific crop and tillage combination occurs on a particular 900-m^2 area. It does, however, indicate that a specific combination of crop type, tillage, and soil exists on a number of 900-m^2 areas within a given county, and we are estimating the location of these specific combinations and the C dynamics associated with them. Table 3 provides an estimate of accuracy for the original data sets to help understand the likelihood of locating crop practices based on the integration of these data sets.

All data were distributed in data layers in a geographic information system. Data layers were integrated in a stepwise progression to form a single spatial data composite. Spatial data layers representing land cover classes, soils, and county boundaries were first combined into a single composite raster data layer (Step d in Fig. 3). This composite layer represents unique combinations of (i) NLCD land cover class, (ii) STATSGO map unit value, and (iii) county FIPS code for each 30-m grid cell (Steps a–c in Fig. 3). ArcGIS 9.1 (ESRI, 2005) was used to project the spatial data sets in a common coordinate system and integrate the data sets into one composite layer. Due to file size limitations in ArcGIS 9.1, a looping procedure within ArcGIS ModelBuilder was developed to process one county at a time.

In a separate step, the NASS and CTIC data were fused together (Step e in Fig. 3) to provide estimates of tillage intensities used per crop type in each county. Area percentages of different tillage methods per crop type per county were applied to the NASS data, and this new integrated product was distributed across respective land areas and soil types according to county delineations and land cover classifications provided by the remote sensing product. For example, the fraction of different tillage intensities from the CTIC data for small grains was applied to each crop that was considered a small grain in the NASS data (e.g., wheat [*Triticum aestivum* L.], rye [*Secale cereal* L.], oat [*Avena sativa* L.], and barley [*Hordeum vulgare* L.]). While our framework included estimates of cropland area from three different sources (i.e., NASS, CTIC, and NLCD), we used the NASS data as the basis for crop area allocation because of its increased delineation of crops and its annual temporal resolution. Estimates of cropland area from the NASS data, aggregated to NLCD land use classes, were greater than the cropland area estimated with remote sensing in the NLCD data across all land use categories (Fig. 4). We anticipate increased accuracy of cropland area at the subcounty level as remote sensing data capture a more diverse and complete set of crop types, as is currently being done with the CDL.

Table 3. Spatial and temporal resolution of the data used.

Data source	Spatial resolution†	Temporal resolution‡	Associated accuracy§
National Agricultural Statistics Service	map scale: county MAD: county	annual	94–99%¶
Conservation Technology Information Center	map scale: county MAD: county	annual; biannual after 1998	90%#
State Soil Geographic database (STATSGO)	map scale: 1:250,000 MAD: 625 ha	average of soil attributes from all soil surveys before 1994	not available
National Land Cover Data	map scale: 30 by 30 m MAD: 0.09 ha	~1992	51%††
Field data on soil C change	plot to field	time soil sample was taken	dependent on sampling method

† Original map scale and the minimum area of delineation (MAD).

‡ Time period represented by estimates or measurements.

§ The percentage of land area accurately represented by the respective estimates or measurements.

¶ Based on range of root mean square error percentages for barley, corn, cotton, sorghum, soybean, and wheat (Prince et al. 2001).

Most counties conduct a sampling transect with a minimum of 480 sample sites per county and have at least a 90% accuracy. Other counties use a local conservation partnership to estimate tillage practices and this method is not amenable to an accuracy assessment (Karen Scanlon, Executive Director, Conservation Technology Information Center, personal communication, 2006).

†† Averaged between assessments of overall accuracy for Level II classification in the Great Lakes (64% accuracy) and Midwest (38% accuracy) regions. Averaged accuracy for Level I classification (e.g., single cropland class vs. higher level classification for separate classes of row crops, small grains, pasture, etc.) was higher at 82.5% accuracy (Wickham et al., 2004).

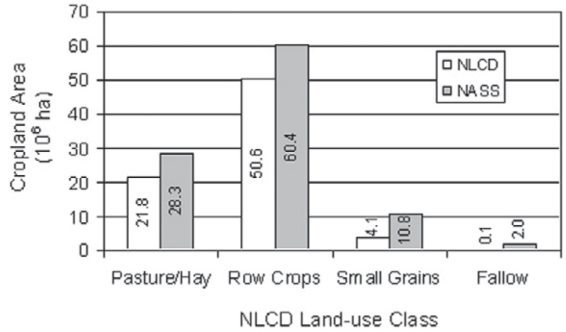

Fig. 4. Comparison of National Land Cover Data (NLCD) cropland area and National Agricultural Statistics Service (NASS) cropland area aggregated to the NLCD land use categories.

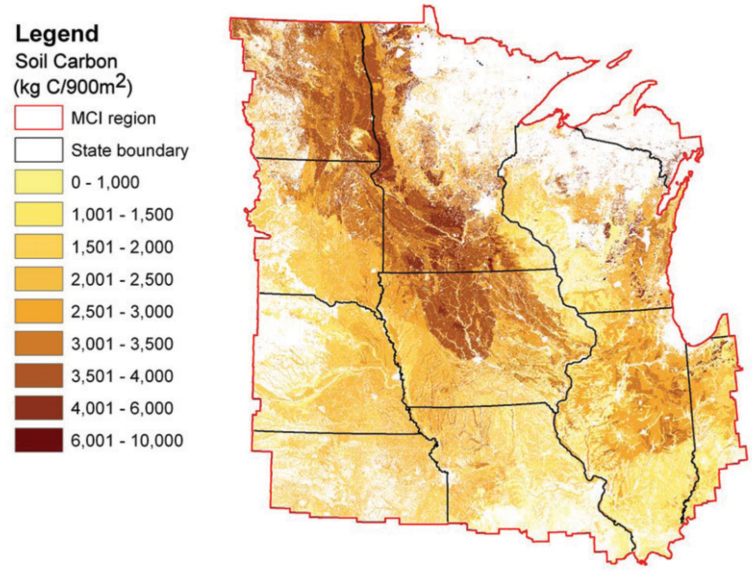

Fig. 5. Estimated soil C content for the Mid-Continent Intensive (MCI) region in 1990. Soil C content is based on historical tillage and cropping practices. The spatial resolution of 900 m^2 coincides with land use categories delineated by the National Land Cover Data (Vogelmann et al., 2001).

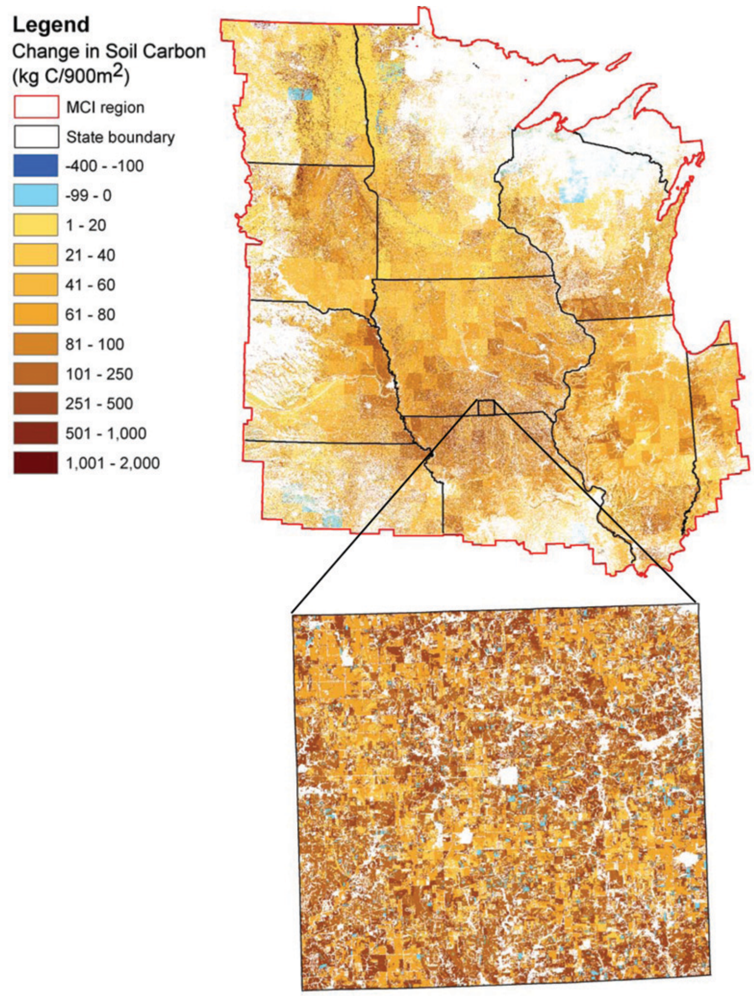

Fig. 6. Cumulative changes in soil C from 1991 to 2000 caused by changes in tillage intensity and crop rotation for the Mid-Continent Intensive (MCI) region. The magnified area is an enhanced view of Wayne County, Iowa. Wayne County includes a diverse set of cropping practices, tillage intensities, and soil types, and illustrates a range of soil C gain and loss at a 900-m^2 resolution within a 10-yr period.

In a third and final step, we applied estimated changes in soil C (Step f, Fig. 3), based on analyses of field data, to changes in crop and tillage management within respective land areas. Soil C accumulation and loss factors were adjusted based on baseline soil C values and then multiplied with initial values of soil C that were associated with the spatial location of unique combinations of crop, tillage, and soil type. The final result includes estimates of soil C flux for the MCI region and estimates of where these fluxes are located. Both the fusion of NASS and CTIC data, discussed above, and estimates of soil C change were computed outside of the ArcGIS data management system using SAS 9.1 (SAS Institute, 2006).

RESULTS

Considering historical changes in tillage intensity and cropping practices, we estimated that soil C within the MCI region and in the baseline year of 1990 was 4117 Tg. This estimate is for agricultural soils to a maximum depth of 3 m or to bedrock. For the 0- to 30-cm depth, we estimated 2128 Tg C (Fig. 5). This latter estimate is 5% larger than the 2025 Tg C estimated using STATSGO data alone (i.e., not considering past changes in tillage and cropping practices). The cumulative change in soil C from 1991 to 2000 on these lands was estimated to be a 70.3 Tg C increase above the 1990 baseline estimate (Fig. 6). Of this net increase in soil C, 33.8 Tg C is attributed to changes in tillage and planted crops, and 36.5 Tg C is attributed to C accumulation on CRP lands.

Because the net increase of 33.8 Tg C is a result of increases in C storage due to reduced tillage and of losses in C storage due to tillage intensification, it is useful to estimate the total of these two components separately. If we completed our analysis without including soil C loss caused by an increase in tillage intensity, the total gain in soil C from 1991 to 2000 on non-CRP lands would be estimated at 45.0 Tg C. With respect to C accounting issues (see West et al., 2004), the difference between estimates with and without soil C losses thereby represents a 25% leakage with time or, stated differently, 75% of the sequestered soil C across the MCI region is "permanent" at this time

Table 4. Annual soil C flux from 1991 to 2000 for aggregated crops in the Mid-Continent Intensive region.

Crop	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	Total
	Mg C yr^{-1}										
Corn and soybean	1,210,363	1,816,476	2,097,169	2,152,714	2,071,263	2,573,636	3,054,658	2,657,298	2,897,578	2,957,719	23,488,875
Small grains	117,322	338,699	435,195	290,910	215,283	454,160	327,074	237,396	82,872	180,878	2,679,788
Other†	33,555	30,740	121,771	−44,619	51,431	48,651	46,748	51,876	36,736	23,879	400,767
Pasture or forage	407,216	519,826	622,693	932,170	472,597	806,718	885,141	884,927	958,669	728,186	7,218,142
Fallow	493	−17,345	2,106	22,039	25,901	−3,985	7,868	8,994	12,811	−7,110	51,772
CRP‡	3,619,319	3,748,926	3,876,738	3,876,738	3,871,892	3,817,476	3,497,668	3,370,668	3,307,208	3,496,948	36,483,581
Total	5,388,267	6,437,322	7,155,672	7,229,952	6,708,367	7,696,656	7,819,158	7,211,159	7,295,873	7,380,499	70,322,926

† Includes sorghum, cotton, sugarcane, sugarbeet, tobacco, peanut, sunflower, bean, lentil, potato, and crops categorized as "other" in the Conservation Technology Information Center data. Positive values represent a net increase in soil C, while negative values represent a net loss of soil C.
‡Conservation Research Program.

scale. Leakage is primarily driven by annual changes in tillage and changes in the land area of harvested crops.

Table 4 shows the total cumulative change of soil C in agricultural lands from 1991 to 2000 by aggregated crop category and by year. The largest contributions to the increase in soil C have been from CRP set-asides and from corn and soybean [*Glycine max* (L.) Merr.] cropping. There is considerable year-to-year variability. Comparing changes in soil C (Table 4) with changes in land area (Table 5) provides insight into probable primary causes of soil C change (e.g., changes in tillage or changes in cropland area). The total evaluated land area in the MCI region, including harvested croplands and CRP lands, increased from 63 to 66 million ha during the 10-yr period (Table 5). This increase is due in part to the Federal Agriculture Improvement and Reform Act of 1996, which eliminated land use restrictions from previous acreage reduction programs and resulted in an increase in harvested soybean acreage (Vesterby and Krupa, 1997).

Most of the additional land area in corn and soybean between 1990 and 2000 was in no-till (Table 5), resulting in soil C accumulation. Adoption of no-till for small grains generally increased as a fraction of the total area in small grains, but the total land area for small grains decreased. The classification representing "other" crops had a small increase in no-till land area, but had significant movement from reduced tillage to conventional tillage in the late 1990s, which offset C gains. Soil C accumulation under pasture or forage lands was primarily due to increased land area in pasture, much of which was under reduced tillage practices. Fallow lands maintained a general increase in no-till adoption and associated C accumulation. Lands set aside under the CRP maintained a steady annual accumulation of soil C, which is consistent with the relatively long-term contracts (~10 yr) associated with these programs. Hence, conservation programs represent a stable, dependable, and more easily predictable source of C accumulation within a portfolio of soil C sequestration strategies.

Table 5. Land area distribution of crop and tillage practices for the period 1990 to 2000.

Tillage†	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
	10^3 ha										
	Corn and soybean										
CT	13,710	13,068	11,413	8,858	11,556	10,780	11,341	10,538	11,457	11,860	13,731
NT	2,086	2,863	4,914	6,288	7,272	7,412	7,388	8,355	8,106	8,593	9,314
RT	18,848	20,285	20,764	20,162	18,876	17,703	19,721	20,991	20,999	20,563	19,185
	Small Grains										
CT	5,911	4,330	4,474	3,729	3,379	3,465	3,533	3,090	2,653	2,934	3,598
NT	407	476	588	733	669	762	981	867	900	736	730
RT	6,834	6,321	6,758	7,282	6,577	5,620	6,052	5,537	4,718	3,689	3,297
	Other‡										
CT	1,666	1,696	1,537	645	1,528	1,440	1,254	1,228	1,320	1,521	1,818
NT	138	178	240	1,407	330	356	362	339	333	334	336
RT	1,334	1,583	1,556	1,213	1,723	1,646	1,614	1,510	1,546	1,320	973
	Pasture or Forage										
CT	2,967	2,985	2,805	2,782	3,129	3,626	3,908	3,782	3,683	4,008	3,845
NT	1,830	1,386	1,324	1,408	2,036	1,390	1,338	1,423	1,484	1,541	1,526
RT	2,016	2,234	2,225	2,276	2,597	2,556	3,209	3,249	3,199	3,014	2,694
	Fallow										
CT	377	382	104	48	318	579	338	280	292	440	404
NT	66	61	12	17	103	200	93	77	95	142	94
RT	576	543	172	182	468	676	467	510	515	541	287
	Set-aside (Conservation Reserve Program)										
	4,345	4,413	4,584	4,760	4,760	4,754	4,696	4,301	4,105	4,016	4,230
Total	63,110	62,802	63,470	61,790	65,320	62,967	66,296	66,079	65,405	65,253	66,065

† CT, conventional tillage; NT, no-till; RT, reduced tillage (ridge till + mulch till + reduced till).

‡ Includes sorghum, cotton, sugarcane, sugarbeet, tobacco, peanut, sunflower, bean, lentil, potato, and crops categorized as "other" in the Conservation Technology Information Center data.

Land areas under no-till increased from 1991 to 2000 for all crop categories with the exception of pasture or forage lands. Land areas under reduced tillage tended to oscillate more and shift among conventional tillage, no-till, and reduced tillage. This dynamic is exemplified within the "other" land use category between 1999 and 2000, where nearly 300,000 ha of land moved from reduced tillage to conventional tillage. These back-and-forth changes among tillage intensities and crop practices, and their effects on soil C, are what we aimed to capture using this soil C accounting methodology. Within our accounting framework, if reduced land area under one crop is picked up under another crop, the C lost in one category will be gained in another category for the same year, based on adoption of the new crop and tillage practice.

DISCUSSION

This study provides a systematic approach for estimating changes in soil C at the regional scale and estimating the subcounty location of these changes. The approach used here relies on empirical relationships among land management, cropping practices, and soil C that were developed directly from analyses of field experiments. Other published methods include the use of default C accumulation factors (Penman et al., 2003) and the use of biogeochemical models. Our results are of the same magnitude as other national and regional estimates, but differences among these estimates exist and we compare these differences below.

Brenner et al. (2001) applied the CENTURY model to Iowa and estimated a 1,475,157 Mg increase in soil C during 1998 due to adoption of reduced tillage practices and a 840,862 Mg C increase on CRP lands. If we aggregate our results for Iowa in 1998, we estimate a 570,464 Mg increase in soil C associated with tillage practices and a 479,424 Mg C increase on CRP lands. For the entire MCI region in 1998, we estimate a 3,840,491 and 3,370,668 Mg C increase associated with tillage practices and CRP lands, respectively.

We attribute the apparent difference between our estimates and those of Brenner et al. (2001) in part to our accounting of soil C losses associated with the periodic alternating of low- and high-intensity tillage practices. For example, our integration of tillage and cropping data indicates an increase of 19.8% in the land area under conventional tillage in Iowa in 1998, a 3.9% increase in land area under reduced tillage, a 23.5% decrease in land under no-till, and a <0.5% change in total land for harvested cropland and CRP lands. Hence, in Iowa in 1998, there was a switch from no-till to conventional and reduced tillage on 468,498 ha. If the loss of soil C associated with the increase in tillage intensity is not considered, we estimate an increase in soil C of 928,439 Mg in 1998 due to changes in tillage. This is a 63% increase above our estimate that includes soil C loss.

Additional possibilities for the difference between regional estimates for Iowa are that (i) our framework was developed for wall-to-wall estimates for the United States and, as such, field data were not compiled and analyzed specifically for Iowa, nor was our framework calibrated specifically for Iowa; (ii) our method does not include an increase in residue production from crop improvement; and (iii) our estimates are a function of initial soil C instead of being based on a first-order decay rate (Brenner et al., 2001) or the potential soil C capacity (see West and Six, 2007).

Eve et al. (2002) and Ogle et al. (2003) completed national-scale estimates of soil C by using the Intergovernmental Panel on Climate Change (IPCC) methodology (Houghton et al., 1997) and by using the Century biogeochemical model (USEPA, 2007). Using the IPCC methodology, Ogle et al. (2003) estimated that U.S. agricultural lands sequestered an average 1.3 ± 5.6 Tg C yr^{-1} between 1982 and 1997. This estimate constitutes an average increase of 10.8 Tg C yr^{-1} on mineral soils minus an average loss of 9.4 Tg C yr^{-1} on organic soils. Using the Century model (USEPA, 2007), average net C sequestration for the United States was estimated to be 11.6 Tg C yr^{-1} between 2000 and 2005. While our research was focused on the MCI region, we also conducted simulations for the entire United States. Our results indicate that average net C accumulation for the United States between 1991 and 2000 was 14.4 Tg C yr^{-1}, of which 6.2 and 8.1 Tg C yr^{-1} was from tillage practices and lands set aside for CRP, respectively.

In comparing estimates for 2000, USEPA (2007) estimated a net accumulation of 11.2 Tg C on U.S. croplands remaining croplands, and our results indicated a net accumulation of 14.7 Tg C, with 7.1 and 7.6 Tg C accumulating due to reduced tillage practices and CRP lands, respectively. These estimates reflect recent changes in soil C and do not represent future potential soil C accumulation following incentives that could potentially be initiated for C management activities (McCarl and Schneider, 2001). Estimates of potential U.S. C sequestration have been estimated at between 60 and 70 Tg C yr^{-1} (Sperow et al., 2003).

CONCLUSIONS

Integration of inventory and remote sensing data can offer improved data sets that spatially delineate production inputs and management occurring on local lands. Continued development of data integration methods is important to the continued improvement of C management and C accounting. The C accounting framework presented here uses inventory data and remote sensing to estimate soil C accumulation and loss at the subcounty level, commensurate with the resolution of Landsat satellite imagery. Our methodology and results allow for comparisons of regional-scale, spatially resolved field and inventory data to annual CO_2 flux data from eddy covariance flux towers. The combination of publicly available data used here, an annual time step, and a transparent methodology is suitable for monitoring changes in soil C at the regional and national scale, while maintaining the resolution necessary on which to base local land management decisions.

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