The Impact of Soil Conservation Policies on Carbon Sequestration in Agricultural Soils of the Central United States

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ABSTRACT

To evaluate the impact of conservation policies on soil organic carbon in agricultural soils, we linked the production and cropping systems information from the 1992 National Resources Inventory (NRI) database and the extensive physical data on soils and climate from the SOILS5 database. These data serve as input for the Erosion Productivity Impact Calculator (EPIC), a biophysical process model calibrated for the conditions and practices prevalent in the study region. EPIC simulations were conducted for NRI sites in a random sample of 11,581 points drawn from the NRI database. From this output we derived a soil organic carbon metamodel that predicts the site-specific annual rate of change of carbon as a function of management practices, soil erosion, initial soil conditions, and geography. By changing management variables for NRI points to reflect alternative policies, the metamodel can predict the site-specific impacts on soil carbon for each policy.

Four policy scenarios were developed: (1) a 1992 baseline policy with CRP, (2) a no-CRP policy, which returned CRP lands to pre-enrollment management, (3) a mandatory T-based policy limiting soil losses to one-T, and (4) a voluntary tillage policy reducing conventional tillage by 50 percent.

Using the NRI database, we estimate that the initial level of carbon sequestered in the soils of the study region is 10,823 Tg. From this level, all policies indicate that agricultural soils will lose carbon. The baseline had an annual loss rate of 14.8 Tg. Eliminating CRP increases the loss rate to 15.7 Tg or a 6 percent increase over the baseline. The T-based policy reduces the annual loss rate to 2.7 Tg or an 80 percent reduction from the baseline. The tillage policy reduces the loss rate to 7.6 Tg or a 50 percent reduction from the baseline. These results indicate that reducing soil erosion, rather than removing land from agricultural production, is the most effective way to increase carbon sequestration and enhance soil quality to preserve the long-term productivity of agricultural soils.

THE IMPACTS OF SOIL CONSERVATION POLICIES ON CARBON SEQUESTRATION IN AGRICULTURAL SOILS OF THE CENTRAL UNITED STATES

Introduction

The pool of organic carbon in soils plays a key role in the carbon cycle and has a large impact on the greenhouse effect (Lal et al., 1995). Soils contain an estimated 1.5×10^{18} g of carbon, or twice as much as the atmosphere and three times the level held in terrestrial vegetation (Post et al., 1990; Schlesinger, 1990). The annual net release of carbon from agriculture has been estimated at 0.8×10^{15} g, or about 14 percent of current fossil fuel emissions (Schlesinger, 1995). In addition to the influence that soil carbon has on global warming, it also plays a key role in determining long-term soil fertility necessary to sustain profitable long-term agricultural production. The ability to sequester carbon in soils by proper tillage and erosion management provides long-term justification for soil conservation programs. However, there is scant information on the changes in soil organic carbon (SOC) that accrue from key soil conservation programs and policies.

In 1986 the Conservation Reserve Program (CRP) began converting highly erodible and other environmentally sensitive land from crop production to perennial grasses or trees. The 1990 Farm Bill mandated conservation compliance to be fully implemented by 1995 for producers participating in federal commodity programs. These policies were not explicitly intended to enhance carbon sequestration in agricultural soils, yet both programs clearly affect SOC on millions of acres.

Farmers' responses to these policies and the resulting effects on SOC are difficult to model across large regions of the United States because of the diverse agricultural practices currently in use. Numerous tillage practices, crop rotations, conservation practices, nutrient management practices, and irrigation types need to be taken into account for effective modeling. Furthermore, large regions have thousands of different soils, diverse topography, and varied climates. Researchers have developed various models and approaches to describe soil carbon dynamics at the field level and from these results have projected policy impacts at the regional level. Donigian et al. (1994) reviewed some of these studies. Noteworthy among these are applications based on biophysical process models such as CENTURY (Parton et al., 1987) and DNDC (Li et al., 1992a, 1992b), as well as the approach by Kern and Johnson (1993) using a geographic information system (GIS) and a simple regression equation. For our purposes, these approaches did not adequately account for the effects of soil erosion or provide the flexibilty to analyze the effect of managment changes such as tillage, crop rotation, or fertrilizer rate.

Carbon losses in eroded soil can be significant, particularly in long-term studies; yet most of these approaches do not adequately model the effects of tillage, crop rotation, and conservation practices on soil erosion. The cumulative impact on SOC of even small annual losses of carbon in eroded soil can become significant after prolonged cultivation and may constitute a large portion of the SOC decrease observed with the initiation of cultivation (Bouwman, 1990; Donigian et al., 1994). Lal (1995) estimates that 20 percent of carbon displaced with eroded soil is decomposed and emitted to the atmosphere. Johnson and Kern (1991) suggest the proportion is approximately 50 percent. The U.S. Environmental Protection Agency, in its report on climate-change mitigation strategies for forest and agricultural sectors, concludes that a more thorough investigation of the impact of no-till practices on SOC levels and better tracking of eroded SOC is needed to quantify the soil conservation policy impacts on SOC levels (USEPA, 1995).

In this paper we present an integrated modeling approach that links a biophysical process model and the 1992 National Resources Inventory (NRI) (USDA/SCS, 1994) in a geographic information system (GIS) to measure SOC dynamics. The NRI is itself linked to the SOILS5 database to provide detailed soil profile information for each sample point. We chose EPIC (Erosion Productivity Impact Calculator) for our biophysical process model to simulate the impacts of alternative production systems on SOC levels (Williams et al., 1988; Sharpley and Williams, 1990). EPIC allows the simultaneous modeling of soil erosion, nutrient fate and cycling, crop growth and soil carbon dynamics, as well as provides extensive flexibility in designing managment systems. Using this framework, we evaluate the impact of CRP, conservation compliance, and conservation tillage policies on carbon sequestration in the agricultural soils of the Central United States.

The NRI provides an ideal database to estimate the total organic carbon sequestered in soils. Kern and Johnson (1993) and Bliss et al. (1995) also base their carbon sequestration studies on the NRI. Given its site-specificity, the NRI is easily incorporated into a GIS framework, and the NRI expansion factors allow statistically valid aggregation. The NRI and other data become input for the EPIC process model and, thus, provide the biophysical and management detail needed for effective spatial analysis at the regional scale.

EPIC is well-suited to simulate the site-specific impacts of alternative production systems on soil erosion, nutrient fate and cycling, crop growth, and soil carbon dynamics. Because these processes are interrelated, an integrated and comprehensive modeling system such as EPIC is critical to adequately capture the impacts. EPIC has been validated and calibrated for a wide variety of conditions, particularly for the conditions and management practices prevalent in our study region (Sharpley and Williams, 1990).

Research Methods

Theoretical Development

In its most basic form, the annual rate of change of soil carbon can be explained by assuming single-pool first-order kinetics (Parton et al., 1996):

$$\frac{dC_t}{dt} = h\alpha - \beta C_t \tag{1}$$

where C_t is the soil organic carbon content at time t, β the decomposition rate of soil carbon, α the addition of carbon to the soil at time t, and h the carbon storage fraction constant. If the rate of change is positive, i.e. $h\alpha > \beta C_t$, then the soil acts as a carbon sink. If the rate of change is negative, i.e. $h\alpha < \beta C_t$, then the soil acts as a source of carbon.

At equilibrium, when additions to soil organic carbon equal losses, then

$$\frac{dC_t}{dt} = 0 \Rightarrow C^* = \frac{h\alpha}{\beta}. \tag{2}$$

That is, the equilibrium carbon content C^* is directly proportional to the carbon accretion factor $h\alpha$, which depends on carbon inputs to soil through plant biomass. In agricultural systems, these inputs are a function of root growth and crop residue (R) and fertilization (N), and R, in turn, is a function of cropping practices (M):

$$h\alpha = g_1(R(M), N). \tag{3}$$

The rate of decomposition (β) depends on intrinsic soil properties (S), cropping practices (M), and other spatial and weather factors (W):

$$\beta = g_2(S, M, W). \tag{4}$$

Finally, C_t is determined by initial soil organic carbon content (C_0), intrinsic soil properties (S), weather factors (W), and erosion (E), whereas erosion is a function of cropping practices, intrinsic soil properties, and weather factors (M, S, W):

$$C_t = g_3(C_0, S, W, E(M, S, W)). \tag{5}$$

Erosion in turn is a function of many of these same factors as shown. Combining equations (3), (4), and (5) we can represent the annual rate of change as

$$\frac{dC_t}{dt} = f(M, N, S, W, C_0). \tag{6}$$

Equation (6) is the theoretical basis for our SOC model that expresses the annual rate of change as a function of management (rotation, tillage, irrigation, fertilization), water and wind erosion, initial carbon status, and location. As we explain, our model is a first-order approximation of a higher order or nonlinear process; therefore, we include C_0 among our regressors for estimating Equation (6). Finally, because our regression model is derived from the output of another model, it is a *metamodel*, and the statistical technique used to estimate the model is *metamodeling* (Kleijnen, 1987).

Metamodeling

Even using current computer technology, conducting EPIC simulations for all 153,869 cropped NRI points in our 12-state study region for each of the policy scenarios would be prohibitive in time and cost. To overcome this limitation we use metamodeling, which involves running biophysical-process model simulations on a manageable subset of the NRI population, then creating a regression model to explain the simulation outcome for environmental indicators such as water and wind erosion, nitrogen runoff and leaching, and SOC.

Metamodels are simple, statistically valid response functions explaining changes in environmental indicators as functions of production and management variables, initial resource settings, and climatic factors. The estimated metamodel is then used to predict changes in environmental indicators at every NRI point in the population. This output is the baseline environmental impact. Alternative policies are analyzed by changing the production and management variables for each NRI point to reflect the new policy, then the site-specific impacts are predicted by the metamodel.

We have developed separate metamodels for nitrate-nitrogen leaching, nitrate-nitrogen runoff, wind erosion, water erosion, and soil organic carbon changes. The development and application of the nitrogen and erosion metamodels can be found in Wu, Lakshminarayan, and Babcock (1996) and Lakshminarayan and Babcock (1996).

Study Region

Our study region includes the Lake States of Michigan, Wisconsin, and Minnesota; the Corn Belt states of Ohio, Indiana, Illinois, Iowa, and Missouri; and the Plains States of North Dakota, South Dakota, Nebraska, and Kansas. This 12-state region accounts for 57 percent of the nation's cropland and large proportions of the nation's corn, soybeans, wheat, and sorghum acreage. In 1991, it produced 89 percent of the nation's corn, 81 percent of the nation's soybeans, 56 percent of the nation's wheat and 56 percent of the nation's sorghum. These four crops plus alfalfa and summer fallow account for about 87.5 percent of the cropland in the study region. Corn and soybeans are the major crops in the Corn Belt and Lake States and account for 72 percent of the cropland in these two regions. Corn and wheat are the major crops of the Plains and account for 51 percent of cropland. In 1992, cropland accounted for 53 percent of all land use in the Corn Belt, 32 percent in the Lake States, and 44 percent in the Northern Plains.

Fourteen major crop rotations were identified in the study region (Table 1). The most common rotations in the Corn Belt and Lake States are corn-soybeans, continuous corn, and corn-soybeans-wheat. The wheat-fallow and wheat-sorghum-fallow rotations were the most popular in the Plains. In 1992, about 37 million acres (17.5 percent) were planted with conservation tillage and approximately 14.5 million acres (6.7 percent) were irrigated in the study region (Table 1).

Data

To obtain the regional coverage and site-specific modeling that effective policy analysis requires, our framework links the extensive physical data on soils and hydrology from the SOILS5 (Soil Interpretation Record System) database, production and cropping systems information from the 1992 NRI database (USDA/SCS, 1994), and the information on fertilizer management practices from the USDA 1992 Cropping Practices Survey (USDA/ERS, 1994).

Our framework uses NRI sample points as the basic unit for policy analysis. The 1992 NRI is the third in a series of surveys by the Natural Resource Conservation Service (NRCS) to determine the status, condition, and trend of the nation's soil, water, and related resources. The sampling method is designed to guarantee that inferences at the regional, state, and sub-state levels can be made in a statistically reliable manner. In our 12-state study region, there are more than 150,000 data points that report corn, soybeans, wheat, sorghum, or legume hay. For each sample point, data are reported for almost 200 attributes, including detailed production and management information. Management data include tillage and conservation practices, irrigation use, and participation in the CRP. The three-year cropping history defines the crop rotation for each point. Each sample point also has an expansion factor that assigns each point the appropriate weight for aggregation purposes.

Unfortunately the 1992 NRI tillage information does not disaggregate conservation tillage sites further into reduced and no-till categories. This distinction is crucial for making accurate site-specific erosion assessments. The Conservation Technology Information Center (CTIC) publishes state-level crop-specific estimates of acres under different tillage methods, including reduced tillage and no-till (CTIC, 1993). Tillage systems that maintain 30 to 70 percent residue cover are considered reduced tillage and systems with residue cover exceeding 70 percent are considered no-till. By using CTIC data for 1992, we computed normalized distributions of reduced and no-till acres by crop and state, then randomly classified all NRI conservation tillage points as either reduced tillage or no-till.

The NRI is linked to the SOILS5 database to provide climatic data and detailed soil profile information for each sample point. The SOILS5 database does not explicitly report the total SOC for each profile; however, it can be derived from the reported data.

Finally, we augmented the management information in the NRI with nutrient management information from the USDA 1992 Cropping Practices Survey. The survey data were used to determine state-level rotation-specific nitrogen and phosphorus application rates.

These data serve as input for the biophysical process model EPIC, the simulation model we use to predict the site-specific impacts of different management practices. Policy impacts on important environmental indicators such as soil erosion, nitrate-nitrogen leaching and runoff, and soil organic carbon are estimated by using EPIC simulations at randomly selected NRI sample points, and then constructing metamodels. Among its many components, EPIC models carbon dynamics for the full soil profile and can track carbon sequestered as soil organic carbon. Furthermore, EPIC estimates carbon losses in soil eroded by water and wind.

SOC Metamodel

EPIC Simulations

To create the SOC metamodel, a 30-year EPIC simulation was conducted for each of 11,581 NRI points in a random sample from the NRI population. Management practices were those from the 1992 baseline, and are discussed in the next section. At each point, levels of SOC (kg m^{-2}) for each year of the simulation were calculated from EPIC soil table data by using

$$C = 10 \sum_{\lambda=1}^{10} \rho_{d\lambda} \, POC_{\lambda}(D_{\lambda-1} - D_{\lambda}). \tag{7}$$

EPIC models the soil profile as 10 different layers and λ indexes these layers. POC_{λ} is the percent organic carbon and $\rho_{d\lambda}$ is the dry bulk density (g cm^{-3}) for each layer. D_{λ} is the depth (m) to the bottom of each layer, where $D_0 = 0$ by definition. The depth to the bottom of each profile is as reported in the SOILS5 database and is highly site dependent. Typical ranges are as little as 0.30 meters for shallow soils to as many as 2 meters or more for deep soils. See Bliss et al. (1995) for an example of the range of depths at the state level.

The result of these simulations is a 30-year time series of SOC at each sample point. In general, these time series appear linear in trend with slight regular fluctuations due to crop rotations. As Figure 1 depicts four of these time series for different sample sites and soils in Iowa. Given their linear nature, we use ordinary least squares regression as a first-order approximation of the higher order or nonlinear process. Our SOC metamodel predicts the annual rate of change in SOC (kg m^{-2} yr^{-1}) at each NRI point as a function of its management, erosion rates, initial soil conditions, and geography. Intuitively, we are fitting a linear function to predict the slopes of the lines in Figure 1.

Soil carbon dynamics are a complex network of processes. To simplify our analysis, we use annual changes in SOC levels as an aggregation of these processes. Specifically, we do not report any data on levels of annual carbon inputs or crop yields; however, these are modeled by EPIC and were analyzed during model development. In EPIC, above- and below-ground crop biomass is the only carbon input to the soil, and decomposition and erosion are the only losses. Crop growth and biomass production occur on the surface and tillage moves crop residues into the soil profile. In the soil profile, EPIC models root biomass production and the conversion of crop residues and dead root biomass into soil organic carbon.

Preliminary analysis of EPIC simulations show that for any given soil, the pool of plant and root biomass and crop residues on the surface and in the profile varied from year to year around an annual average, with no statistically valid trend. In the long run, carbon inputs could be modeled accurately as simple annual averages that depend primarily on crop rotation and fertilization. Furthermore, the magnitude of the plant biomass and crop residue pool of carbon inputs was relatively small compared with total SOC levels (less than 3% at the highest). Finally, the accuracy of EPIC crop yields is generally quite good when compared with actual annual averages and the estimates of other models (Touré et al., 1994; Geleta et al., 1994; Sharpley and Williams, 1990).

SOC Metamodel and Coefficients

Using the EPIC results, the SOC metamodel, theoretically developed as Equation (6), was estimated as

$$\frac{dC}{dt} = \beta_0 + \sum_{i=1}^{13} \beta_i D_{rot} + \sum_{j=14}^{15} \beta_j D_{till} + \beta_{16} D_{irg} + \beta_{17} N + \beta_{18} EOC_{water} \\ + \beta_{19} EOC_{wind} + \beta_{20} \rho_{OC_1} + \beta_{21} C_1 + \beta_{22} LAT + \beta_{23} LONG + \mu \, . \tag{8}$$

D_{rot}, D_{till} and D_{irg} are dummy variables for rotation, tillage, and irrigation. N is the rate of nitrogen fertilization (kg ha^{-1} yr^{-1}). EOC_{water} and EOC_{wind} are the loss rates (t ha^{-1} yr^{-1}) of organic carbon lost with soil eroded by water and wind. These rates are calculated by

$$EOC_{water} = E_{water} POC_1 \, , \tag{9}$$

$$EOC_{wind} = E_{wind} POC_1 \, . \tag{10}$$

E_{water} and E_{wind} are the average annual rates of water and wind erosion (t ha^{-1} yr^{-1}), and POC_1 is the percent organic carbon for the first layer (A horizon) as reported in the NRI. Erosion rates are determined by the water and wind erosion metamodels (Lakshminarayan and Babcock, 1996). To convert organic matter as reported in the NRI to organic carbon, we use 57.47 percent as the conversion factor.

The organic carbon density ρ_{OC1} (g cm^{-3}) of the first layer is calculated by

$$\rho_{OC_1} = POC_1 \rho_d \tag{11}$$

$$\rho_d = \rho_m - 0.06 \, . \tag{12}$$

Because the NRI reports the moist bulk density ρ_m (33 kPa bulk density), we use Equation (12) to convert to the dry bulk density ρ_d. Kern and Johnson (1993) derived (12) by analyzing the National Soil Survey Laboratory Pedon Database; they reported $R^2 = 0.96$ for $n = 44,824$. C_1 is the SOC (kg m^{-2}) sequestered in the first layer and is calculated by

$$C_1 = 25.4\, D_1 \rho_{OC_1}. \tag{13}$$

where D_1 is the depth to the bottom of the first layer. Because the NRI reports depth as inches, the 25.4 factor converts to metric units.

LAT and LONG are the latitude and longitude of the nearest weather station reported in the weather database. These serve as proxies because the actual latitude and longitude of NRI points are not public information. By overlaying the weather map grid on the NRI point map and then using the Thiessen polygon technique, we identified NRI points close to each weather station and imputed the latitude and longitude of that weather station to all NRI points in the polygon. These location variables capture many of the climatic effects, primarily temperature and rainfall.

Table 2 reports the coefficient values of the metamodel regression. Judging from the R^2 and the root mean square error, the estimated model fits the data well. Furthermore, the signs of the coefficients are consistent with theory.

Policy Scenarios

To estimate the impacts of alternative policies, we developed four scenarios: (1) the 1992 *baseline policy*, which includes CRP; (2) a *no-CRP policy* for which the cropping practices on CRP lands are switched to their pre-enrollment practices; (3) a mandatory *T-based policy*, which limits soil loss to be below the site-specific soil loss tolerance standard T; and (4) a voluntary conservation *tillage policy*, which switches 50 percent of NRI points farmed with conventional tillage to conservation tillage (reduced and no-till). The impact of the no-CRP, T-based, and tillage policies on carbon sequestration in agricultural soils is the difference in the net SOC levels between the 1992 baseline and the respective scenarios.

The baseline policy uses management variables for each sample point as reported in the 1992 NRI. Our analysis of the impacts of CRP only include data through the 11th sign-up, because this is when the 1992 NRI ends reporting on CRP participation. Because 94 percent of total CRP acres were enrolled in the first 11 sign-ups, this limitation is relatively minor. In addition, our analysis of CRP includes only those points for which the 1992 NRI reports the contracted cover as grasses and legumes. Other CRP contracted covers, such as trees or wildlife and components, were relatively small in the study region. Management practices used for sample points enrolled in CRP included no tillage and no fertilization for the entire 30-year simulation. In the Corn Belt and Lake States, the simulated crop for CRP points was summer pasture, whereas in the Plains States, EPIC simulations used the crop parameters for rangeland.

For the no-CRP policy, 1992 management practices are used for all sample points, except for those enrolled in CRP. Cropping practices for CRP points were switched to their pre-enrollment practices, thus returning sample points to their pre-CRP use. Tillage, conservation, and irrigation practices were as reported in the NRI.

For the T-based policy, management variables are taken from the 1992 NRI, except for those sample points not meeting the one-T soil loss standard. For these points, approved conservation practices are imputed by a simple algorithm so that annual soil erosion falls below T, the maximum level of acceptable loss determined by the NRCS for that site. Crop rotations are held constant and, as a result, a few sites still do not meet the one-T standard, despite using no-till and all conservation practices (strip cropping, contouring, and terracing). Assuming a negligible level of voluntary conservation compliance was implemented before 1992, this scenario captures the impact of conservation compliance based on T. Finally, sample points enrolled in CRP are treated as in the baseline.

The voluntary tillage policy captures the impact of a 50 percent reduction in the use of conventional tillage. Again, 1992 NRI management practices are used for sample points, except for those reporting conventional tillage. These sample points are randomly switched to reduced tillage and no-till so that an overall 50 percent reduction in the use of conventional tillage results in each state. Again, sample points enrolled in CRP are treated as in the baseline.

Results

Initial Level of SOC in Agricultural Soils

To start the system, we needed an estimate of the initial level of carbon sequestered in the study region. Each NRI sample point is linked to a soil profile in the SOILS5 database. The SOILS5 database does not explicitly report the total SOC for each profile, but it can be calculated from the reported data. The depth to the top and bottom of each layer, and the high and low range for organic matter and moist bulk density, are reported for each layer in a profile. From these, the total SOC sequestered in the soil profile at each NRI point can be determined by

$$POC_{\lambda} = \frac{0.5747}{2}(OML_{\lambda} + OMH_{\lambda}), \tag{14}$$

$$\rho_{d\lambda} = \left[\tfrac{1}{2} (BDL_{\lambda} + BDH_{\lambda}) \right] - 0.06, \tag{15}$$

$$SOC_{n} = \sum_{\lambda = 1}^{L} POC_{\lambda} \rho_{d\lambda} R_{\lambda} (D_{\lambda - 1} - D_{\lambda}) . \tag{16}$$

Again, λ indexes soil layers, with each NRI point having L layers, and n indexes NRI points, with a total of N points in the study region. In Equation (14) OML and OMH are the low and high ranges for the percent organic matter reported for each NRI soil layer. The simple average of these and the 57.47 percent conversion factor are used to obtain the percent organic carbon (POC) for each layer.

In Equation (15), BDL and BDH are the low and high ranges for the moist (33 kPa) bulk density reported for each layer. Again, the simple average and the 0.06 conversion constant of Kern and Johnson (1993) are used to obtain the dry bulk density (ρ_d) for each layer.

In Equation (16), R is the rock fragment correction factor for each layer derived by Bliss et al. (1995). It removes from calculations of SOC all coarse matter greater than 2 mm D is the depth (m) to the bottom of each layer and $D_0 = 0$ by definition. Equation (16) calculates the SOC (kg/m^{-2}) for each NRI point as the sum of the SOC in each layer, corrected for coarse matter content in each layer.

Finally, we used Equation (17) to calculate the total carbon sequestered in the agricultural soils of the study region as SOC:

$$SOC_{1992} = \sum_{n = 1}^{N} X_{n} SOC_{n} , \tag{17}$$

where X_n is the appropriate expansion factor (m^2) for each NRI point. Table 3 reports the results of our calculations. Our results for the total SOC only include data for agricultural soils and, therefore, are lower than the results reported by Bliss et al. (1995) for these states. The SOC per unit area reported in Table 3 is comparable to that reported by Bliss et al. (1995).

Empirical Comparisons

Figures 2 and 3 depict the distributions of the annual rates of change estimated by the metamodel for the baseline scenario. In Figure 2, conventional tillage includes both fall and spring plow. Figure 3 illustrates only the most common rotations, and the corn-soybeans rotation includes the data for the corn-corn-soybeans and soybeans-soybeans-corn rotations as well. These distributions are consistent with empirical studies reported in the literature for wheat and continuous grass in Colorado (Wood et al., 1991); corn in Kentucky (Blevins et al., 1983); and corn, soybean, and sorghum rotations in Kansas (Havlin et al., 1990). Li (1995) reports rates predicted by DNDC for soybeans in Iowa, Illinois, and Nebraska that are consistent with the SOC metamodel predictions.

Policy Comparisons

To compare the impacts of each policy, the necessary management parameters were specified for all sample points to coincide with each policy. The coefficients of the metamodel were then applied to the NRI population and the point-specific annual rate of change in SOC predicted under each policy. The policy-specific projected point-level impact on SOC levels after 30 years was calculated by

$$SOC_n^{2022} = SOC_n^{1992} + 30\frac{dC_n}{dt}. \tag{18}$$

Again, n indexes NRI points. The projected SOC in 2022 for each point is simply the sum of the initial SOC in 1992 and the 30-year cumulative change predicted by the SOC metamodel. These point-level impacts were then aggregated for the whole study region by

$$SOC_{2022} = \sum_{n=1}^{N} X_n SOC_n^{2022}. \tag{19}$$

The results for the baseline and the three alternative policies are reported in Table 4. Figure 4 illustrates these results with a time series plot. All scenarios indicate that agricultural soils are net sources of carbon. Beginning from the initial level of 10,823 Tg in the study region, the baseline predicts an annual loss rate of 14.8 Tg. If CRP lands are switched back to pre-enrollment production practices, the annual loss rate increases to 15.7 Tg. Thus the contribution of CRP is an annual reduction of 0.9 Tg in the baseline SOC losses. With a T-based policy, the predicted annual loss rate is only 2.7 Tg or an 80 percent reduction in annual baseline SOC losses. As mentioned previously, crop rotations were not changed under the T-based policy, and some sites still did not meet the one-T criterion. If sites were brought into compliance by also changing crop rotations, the T-based policy would make agricultural soils net sinks of carbon. The result of a 50 percent decrease in conventional tillage is a predicted annual loss rate of 7.6 Tg or a 50 percent reduction in annual baseline SOC losses. The impact of CRP is much smaller because the land area it impacts is far less than the area affected by the tillage policy or the T-based policy. Figure 5 is a GIS map illustrating the 1992 initial and 2022 projected spatial distribution of carbon sequestration under the baseline policy.

Discussion and Conclusion

Our results are consistent with those reported by Kern and Johnson (1993) for different levels of conservation tillage adoption. They reported no scenarios that indicated a net increase in SOC sequestration, unless the effects of reduced fuel consumption were included. Donigian et al. (1994) used CENTURY for a similar study and reported agricultural soils as net carbon sinks; however, they believe that a projected 1.5 percent annual increase in crop yields drives this result. Furthermore, CENTURY did not account for the effects of soil erosion. They report that this omission of erosion impacts needs 0reconsideration for future refinements of CENTURY, particularly for modeling the impact of tillage policies.

Management practices, soil erosion, and initial carbon levels are the key components of the SOC metamodel. Our SOC metamodel is theoretically consistent with other models of organic matter dynamics (Parton et al., 1996). Our SOC metamodel is also empirically consistent with long-term studies. The conclusion of long-term tillage studies of Great Plains soils is that the observed decreases in SOC result from (1) increased aeration due to tillage and (2) loss of topsoil rich in organic matter due to erosion (Haas et al., 1957; Bauer and Black, 1981; Tiessen et al. 1982).

Lal (1995) discusses the importance of soil erosion in global carbon dynamics. He estimates that globally soil erosion displaces 5.7×10^{15} g of carbon (organic and inorganic) annually from terrestrial ecosystems. He estimates that 10 percent of this ends in the ocean and 1.14×10^{15} g is emitted to the atmosphere. Not surprisingly, Ritchie (1989) finds that the carbon content of sediments accumulating in reservoirs in the United States is highly correlated with the carbon content of the A horizon of the soils in each watershed. He estimates that the global rate of carbon sequestration in reservoirs from eroded soil deposition is $0.2\text{-}0.3 \times 10^{15}$ g of carbon annually.

The policy implications of this study are not surprising. Effective policies that reduce soil erosion and enhance soil quality with good agricultural stewardship will also increase carbon sequestration. It is satisfying to have additional evidence that pursuing more immediate and pressing objectives, such as stabilizing producer income and improving water quality, also has positive benefits for long-term concerns such as sustaining productivity and mitigating global climate change. Increased carbon sequestration was not the objective of CRP or conservation policies; however, these policies contribute to SOC accumulation and enhanced soil quality. The results of this study indicate that reducing soil erosion is a more effective way to increase carbon sequestration in agricultural soils than removing the land from agricultural production.

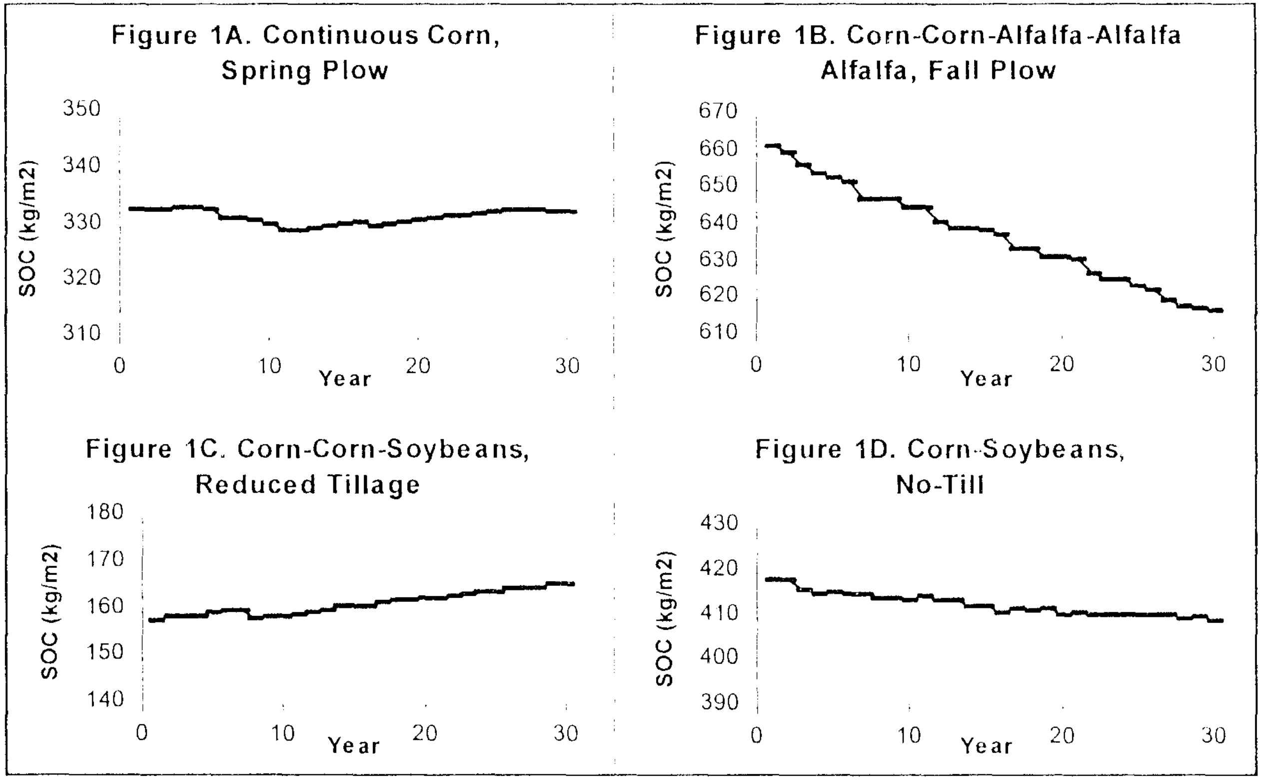

Figure 1. SOC dynamics under baseline practices at four different NRI sample points and soils in Iowa. 1A: Judson (NRI pointer 217917, psu 6238, point 99). 1B: Okoboji (NRI pointer 219068, psu 2956, point 3). 1C: Clarion (NRI pointer 218530, psu 6491, point 3). 1D: Colo (NRI pointer 218441, psu 3578, point 3).

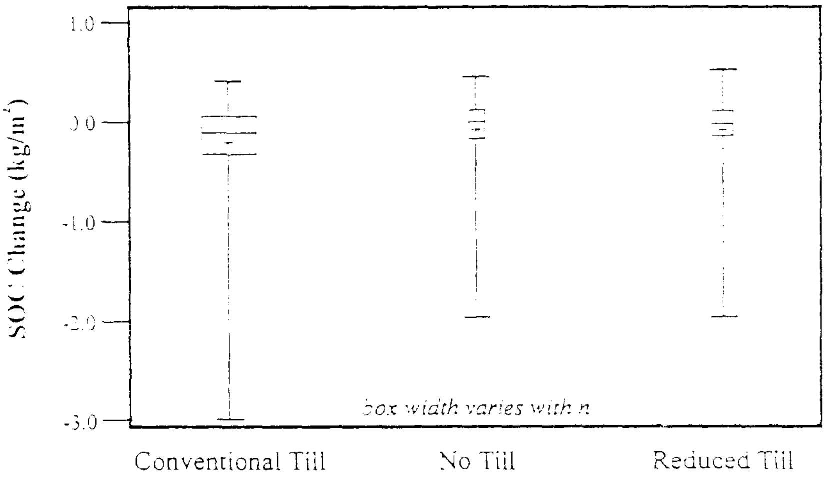

Figure 2. Annual cropland soil organic carbon change by tillage

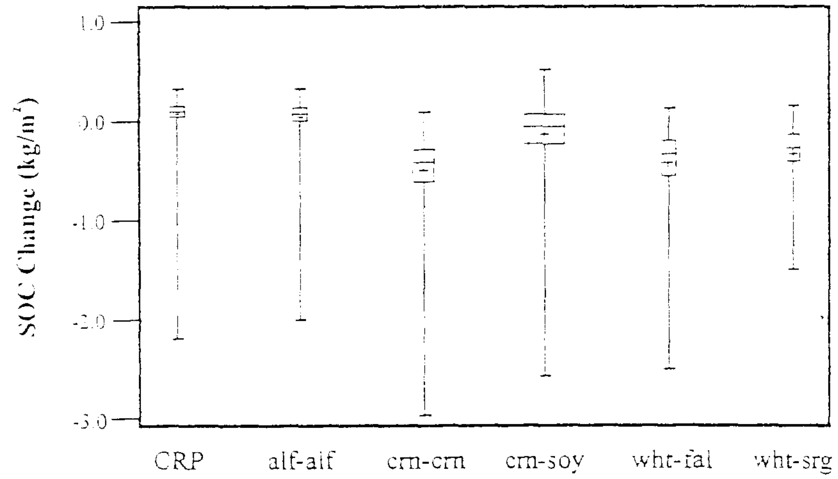

Figure 3. Annual cropland soil organic carbon change by rotation

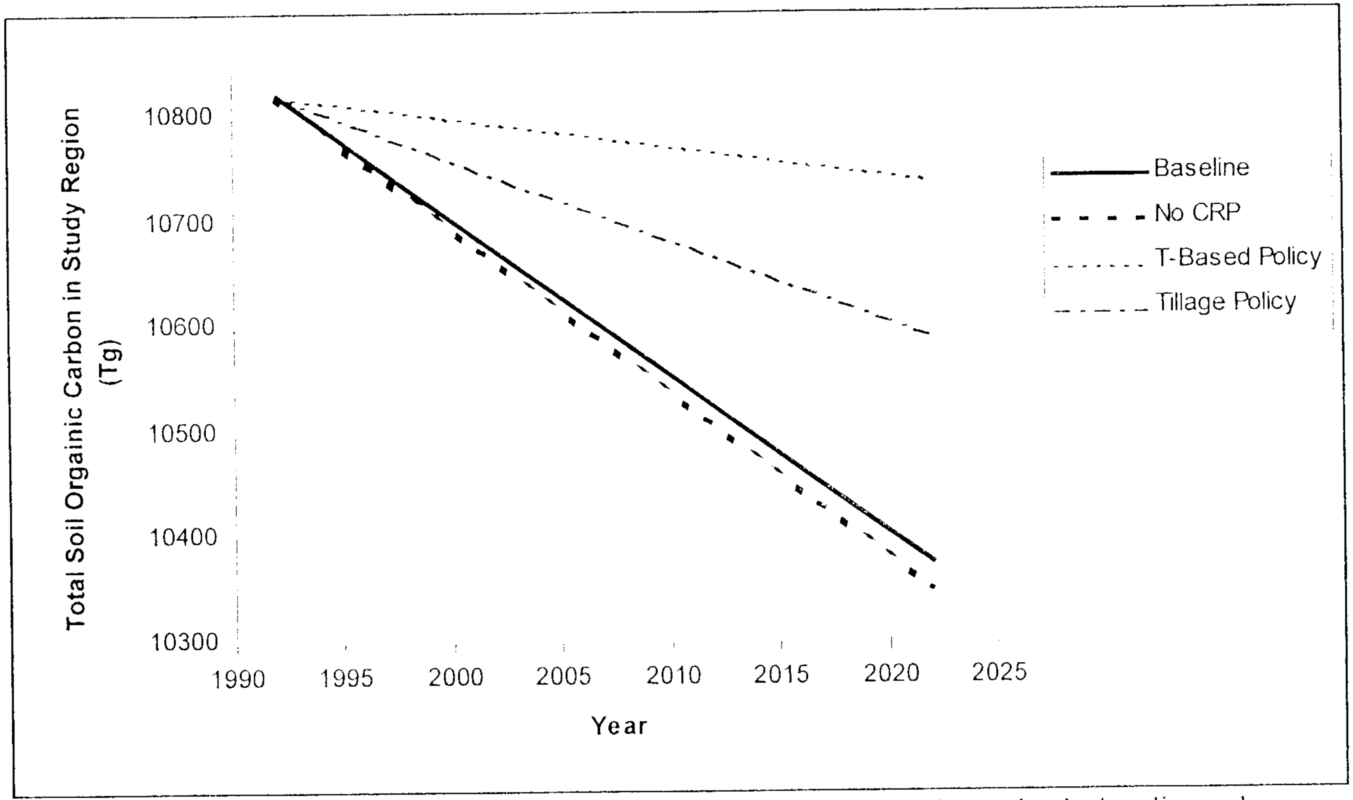

Figure 4. Time series comparing the total SOC sequestered in the study region under the baseline and alternative scenarious.

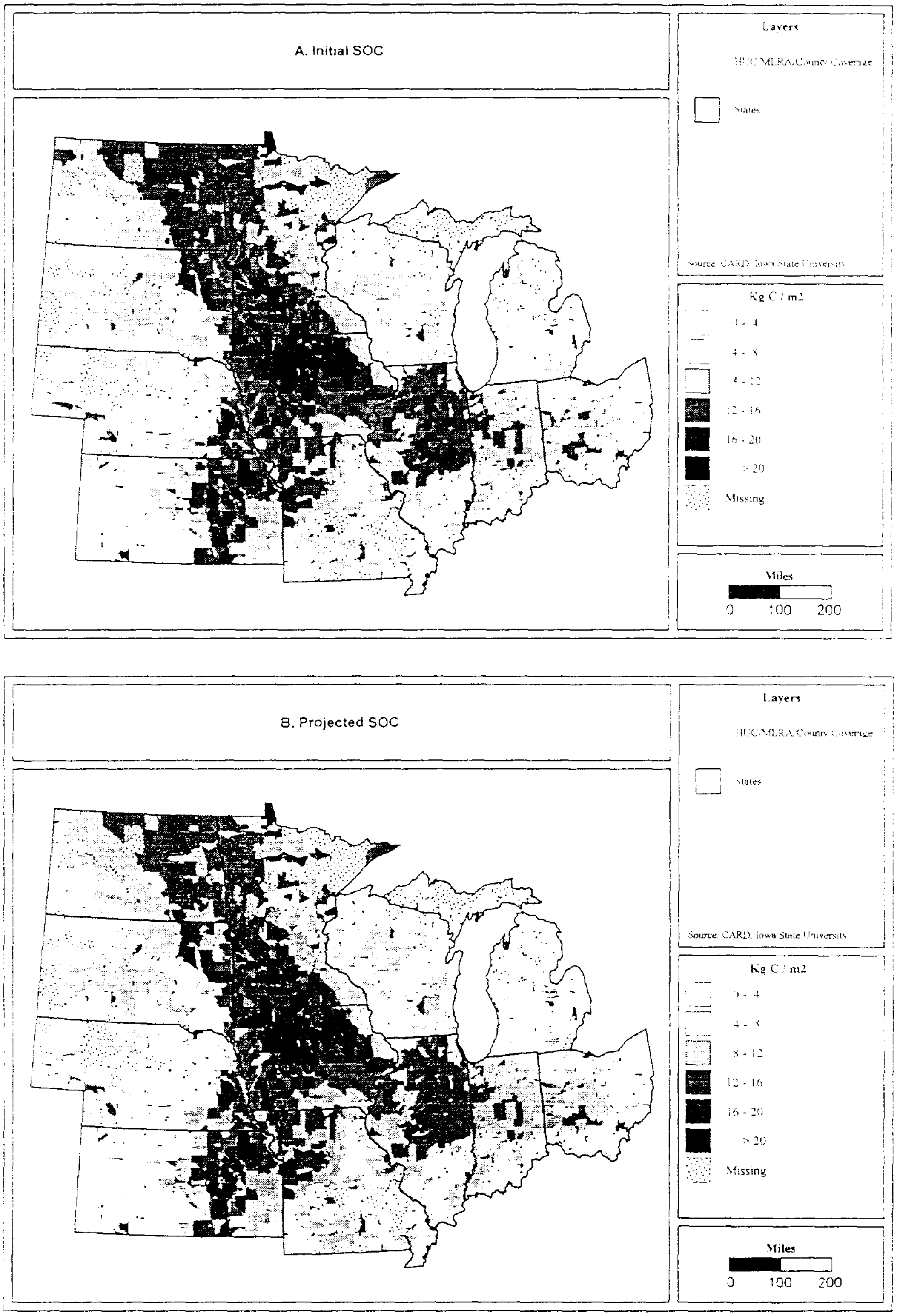

Figure 5. 1992 SOC levels and 2022 projected levels under 1992 NRI baseline.

Table 1. Distribution of Cropland by Management Practices, 1992

Practice	ALL	IL	IN	IA	MO	OH	MI	MN	WI	KS	NE	ND	SD
Crop Rotation	----------	----------	----------	----------	----------	*(percent)*	----------	----------	----------	----------	----------	----------	----------
Continuous Corn	11.8	10.0	12.8	15.1	3.0	7.8	23.0	10.2	25.0	4.8	29.0	2.8	11.4
Continuous Soyb	2.0	1.1	3.2	1.7	10.0	2.4	2.0	2.3	0.9	0.9	1.2	0.5	1.4
Continuous Wheat	7.1	0.1	0.2	0.0	1.1	0.6	1.8	8.5	0.3	15.5	3.4	25.5	9.6
Continuous Sorg	0.2	0.0	0.0	0.0	0.5	0.0	0.1	0.0	0.1	0.1	0.6	0.0	0.6
Corn-Soyb	23.8	55.8	43.3	49.8	17.9	28.8	12.2	28.7	4.6	2.3	18.4	0.6	16.1
Corn-Corn-Soyb	4.4	8.3	13.0	11.6	5.0	5.1	5.5	4.7	2.9	0.0	0.0	0.0	0.0
Corn-Soyb-Wheat	6.2	14.2	11.2	0.2	21.8	27.1	11.0	7.3	1.1	0.0	0.0	0.0	0.0
Soyb-Soyb-Corn	1.7	2.1	3.3	2.3	4.8	4.8	2.2	3.6	0.7	0.0	0.0	0.0	0.0
Wheat-Fallow	5.5	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.0	16.7	7.9	16.7	8.6
Wheat-Sorg-Fallow	5.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.5	5.9	10.0	7.4
Wheat-Soyb	2.5	0.2	0.5	0.0	1.1	1.0	0.8	1.7	0.1	6.1	2.3	4.9	7.4
Wheat-Sorg	2.6	0.0	0.0	0.0	0.3	0.0	0.0	0.0		13.0	8.1	0.1	2.2
Alfalfa-Alfa-Alfa	7.5	2.3	3.0	5.9	7.2	10.3	16.1	8.8	30.7	2.3	6.8	5.0	11.5
Corn-Corn-Alfalfa	1.8	1.2	0.5	2.0	0.8	2.2	2.1	2.8	11.9	0.3	1.6	0.2	1.3
Others	10.2	1.9	6.0	3.7	15.6	7.3	20.3	13.0	15.8	3.7	8.2	23.2	12.9
CRP	7.2	2.9	3.0	7.8	10.8	2.6	2.8	7.8	5.8	9.7	6.6	10.5	9.7
Irrigation Practice													
Nonirrigated	93.3	99.2	98.7	99.4	92.5	99.6	94.7	97.9	96.4	86.9	61.2	99.0	97.1
Irrigated	6.7	0.8	1.3	0.6	7.5	0.4	5.3	2.1	3.6	13.1	38.8	1.0	2.9
Tillage Practice													
Conventional till	82.6	75.6	76.5	59.6	87.7	88.6	86.6	92.7	90.4	81.9	80.5	96.7	86.0
Reduced till	11.6	13.8	7.3	27.1	6.9	3.8	7.8	6.4	7.9	15.9	14.6	2.9	11.1
No-till	5.9	10.7	16.2	13.3	5.5	7.5	5.6	0.9	1.8	2.2	4.8	0.3	2.9

Source: 1992 NRI and the 1992 CTIC databases.

Table 2. SOC Metamodel Coefficients[a].

Regressor	Coefficient	t Statistic[b]
Intercept	-10.959	-21.583
Rotation[c]		
Continuous Corn	-4.150	-21.677
Continuous Soybeans	3.561	21.254
Continuous Wheat	-1.700	-11.400
Corn-Soybeans	1.001	7.340
Corn-Corn-Soybeans	-0.601	-3.636
Corn-Soybeans-Wheat	0.057	0.385
Soybeans-Soybeans-Corn	2.113	12.506
Wheat-Fallow	-2.622	-17.973
Wheat-Sorghum-Fallow	-2.422	-16.938
Wheat-Soybeans	0.967	6.341
Wheat-Sorghum	-3.337	-20.329
Corn-Corn-Alfalfa-Alfalfa-Alfalfa	-1.181	-5.914
CRP (Summer Pasture/Range)	0.430	2.956
Tillage[d]		
Reduced Tillage	0.468	8.497
No-Till	0.326	4.507
Irrigation		
Irrigated	-1.026	-13.242
Fertilization		
Nitrogen Rate (kg ha^{-1})	0.0101	9.846
Erosion		
Water Eroded Organic Carbon (t ha^{-1} yr^{-1})	-0.0627	-100.039
Wind Eroded Organic Carbon (t ha^{-1} yr^{-1})	-0.0901	-77.875
Initial Carbon		
Organic Carbon Density (g cm^{-3})	-0.3278	-11.942
SOC in A Horizon (kg m^{-2})	-0.0091	-19.305
Location		
Latitude	0.0857	11.418
Longitude	0.1007	22.081

[a] $R^2 = 0.75$; n = 11,581; Root Mean Square Error = 0.1788.

[b] The 1%, 5%, and 10% critical values for the t statistic are 2.58, 1.96, and 1.65.

[c] Reference: Continuous Alfalfa.

[d] Reference: Conventional Tillage (fall or spring plow).

Table 3. Initial Cropland SOC Levels

State / Region	Area (ha)	Total SOC (Tg C)	SOC per unit area (Kg C m^{-2})
Indiana	5,612,308	558	9.9
Iowa	10,909,838	2,049	18.8
Missouri	5,980,567	602	10.1
Ohio	4,945,466	424	8.6
Cornbelt	37,486,113	4,861	13.0
Minnesota	9,357,854	1,603	17.1
Michigan	3,727,733	226	6.1
Wisconsin	4,632,834	352	7.6
Lake States	17,718,421	2,182	12.3
Kansas	11,903,887	982	8.2
Nebraska	8,331,417	723	8.7
North Dakota	11,188,866	1,342	12.0
South Dakota	7,351,619	734	10.0
N. Plains	38,775,789	3,781	9.8
Study Region	93,980,324	10,823	11.5

Table 4. Projected Net Annual Loss Rate and Total SOC of Cropland Under Alternative Policies

State / Region	Baseline with CRP		Baseline, no-CRP		T-based policy		Tillage policy	
	Annual Change	Total SOC	Annual Change	Total SOC	Annual Change	Total SOC	Annual Change	Total SOC
	----------	----------	----------	---------- Tg of C	----------	----------	----------	----------
Illinois	-1.05	1,197	-1.05	1,197	-0.11	1,225	-0.40	1,216
Indiana	-0.43	545	-0.44	545	-0.09	555	-0.16	553
Iowa	-2.38	1,977	-2.44	1,975	-0.91	2,021	-1.61	2,000
Missouri	-0.29	593	-0.26	594	0.27	610	0.06	604
Ohio	-0.52	409	-0.52	409	-0.24	417	-0.29	416
Corn Belt	-4.67	4,720	-4.71	4,719	-1.08	4,828	-2.40	4,788
Minnesota	-1.87	1,547	-1.94	1,545	-0.02	1,603	-0.82	1,579
Michigan	-0.42	214	-0.44	213	-0.24	219	-0.28	218
Wisconsin	-0.69	331	-0.74	330	-0.39	340	-0.49	337
Lake States	-2.99	2,092	-3.11	2,088	-0.65	2,162	-1.60	2,134
Kansas	-1.88	926	-2.13	918	-0.48	968	-1.00	952
Nebraska	-1.62	674	-1.74	671	-0.30	714	-0.92	695
North Dakota	-2.68	1,262	-2.91	1,255	-0.35	1,332	-1.39	1,301
South Dakota	-0.99	704	-1.12	700	0.17	739	-0.31	724
N. Plains	-7.17	3,566	-7.90	3,544	-0.95	3,752	-3.62	3,672
Study Region	-14.83	10,378	-15.71	10,352	-2.68	10,743	-7.62	10,594

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