

**SPECIAL SECTION: THE ROLE OF
CONSERVATION AGRICULTURAL PRACTICES
ON REDUCING GREENHOUSE GAS EMISSIONS
AND ENHANCING C SEQUESTRATION**

Soil carbon sequestration potential and the identification of hotspots in the eastern Corn Belt of the United States

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Abstract

Soil C sequestration is a significant CO₂ mitigation strategy, but precise assessments of sequestration require spatially explicit modeling of potential changes in soil organic C (SOC) in response to soil, climate, land condition, and management interactions. We assessed the SOC sequestration potential of the eastern Corn Belt (ECB) in the United States (Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia) in response to the adoption of conservation farming practices and land use change (pasture and forestation) using the SOCRATES model. Input data was provided through an intersection of the State Soil Geographic database, National Land Cover Database, and a PRISM (<https://prism.oregonstate.edu>) climate surface. At the end of the 20th century, the 15.3 Mha of cropped soils in the ECB contained 632 Tg C, an estimated reduction of 52% since the introduction of agriculture in the mid 1800s. Complete adoption of no-tillage practices on prime cropland would potentially recover 147 Tg SOC over 20 yr, whereas a continuation of conventional tillage would produce a loss of 35 Tg SOC over that period. Sequestration hotspots (>500 Gg increase in SOC) under no-tillage cover 2.3 Mha providing 28 Tg C over 20 yr. The conversion of marginal (nonprime) agricultural lands to forests would yield an additional 13 Tg C in SOC and 381 Tg C in aboveground biomass. The rehabilitation of minelands to forest would yield an additional 4 Tg C in SOC and 42 Tg C in biomass. Opportunities to sequester C in the ECB via tillage and reforestation are substantial and should be incorporated into regional and national climate change mitigation strategies.

Abbreviations: ECB, eastern Corn Belt; NCR, North Central Region; NLCD, National Land Cover Database; NPP, net primary production; OC, organic carbon; SOC, soil organic carbon; STATSGO, State Soil Geographic database.

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1 | INTRODUCTION

Soils constitute the largest terrestrial sink for organic C (OC) (Batjes, 1996). With half of all soil organic C (SOC) in managed ecosystems lost to the atmosphere during the past two centuries (Sanderman et al., 2017), the opportunity to recapture some portion provides a significant capacity to mitigate global warming (McCarl et al., 2007; Paustian et al., 2016). Improved management practices and land use change can potentially increase SOC storage at a large scale (Griscom et al., 2017; Lal, 2004; Paustian et al., 2016). For example, the “4 per 1000” initiative (Minasny et al., 2017) announced at the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties in Paris in December 2015 has provided renewed interest globally in the ability of soils to sequester C and mitigate global warming. In cropping systems, conservation tillage has been widely promoted (Palm et al., 2014), as has the rehabilitation of marginal lands to permanent perennial vegetation (Griscom et al., 2017; Paustian et al., 1997). The restoration of drastically disturbed soils (e.g., minesites) also offers potential for soil C sequestration (Lal, 2001).

Evaluation of regional capacities for additional SOC storage requires knowledge of potential sequestration by conservation tillage or land use change practices within different soil–climate locations. Previous evaluations for the eastern Corn Belt (ECB) of the United States (Indiana, Kentucky, Maryland, Michigan, Ohio, Pennsylvania, and West Virginia) have been limited by the use of single C sequestration rates for specific land managements across multiple soil types (Tan et al., 2006). For example, using existing soil attribute databases such as the State Soil Geographic database (STATSGO) to provide average values for SOC across a soil mapping unit ignores the influence of local climate, current land use, and soil condition, which can be major determinants of direction and rates of SOC change.

We developed a spatially explicit simulation methodology to evaluate regional SOC change by merging STATSGO (USDA-NRCS, 1995) and the National Land Cover Database (NLCD; Vogelmann et al., 2001) to estimate baseline SOC stocks in the U.S. ECB before the widespread introduction of conservation tillage practices. We then examined the 20-yr sequestration potential for SOC upon complete adoption of conservation tillage on prime farmland and pastures or forestation on marginal lands. In addition, our analysis identified high potential hotspots for maximizing soil C sequestration within the ECB.

Core Ideas

- Soil organic C (0–30 cm) in the eastern Corn Belt croplands declined by 52% (632 Tg) since the mid 1800s.
- No-tillage practices on prime cropland potentially recovers 147 Tg soil C over 20 yr.
- Soil organic C sequestration hotspots (>500 Gg C increase) under no-tillage cover 2.3 Mha and produce 28 Tg C.

2 | MATERIALS AND METHODS

2.1 | Model specifications

The influence of temperature, moisture, and soil texture on SOC dynamics are well understood (Krull et al., 2003), and simulation models have provided successful representations of SOC change for regional assessments (e.g., Easter et al., 2007; Falloon & Smith, 2002; Grace, Colunga-Garcia, et al., 2006). We used SOCRATES (Grace, Ladd, et al., 2006), a process-based simulation model designed to estimate changes in topsoil OC in response to ecosystem productivity with a minimum dataset of soil, climate, and biological inputs. SOCRATES has been validated against observed SOC data from 18 long-term crop, pasture, and afforestation trials from North America, Europe, and Australia (Grace, Ladd, et al., 2006), where SOC and ancillary climate have been monitored, including seven long-term datasets from within or adjacent to the ECB region.

SOCRATES uses a weekly time step for SOC turnover. Minimum driving variables are annual precipitation (mm), mean annual temperature (°C), soil clay content (%) or cation exchange capacity (mmol kg⁻¹), initial SOC (%), and bulk density (g cm⁻³). Carbon inputs are a function of net primary production (NPP) based on a relatively simple climate specific derivation of Leith (1975). Initial SOC is not an essential input if land use history is known so that a long-term equilibrium simulation can derive the respective masses of the SOC pools. To convert the 0 to 10-cm SOC outputs from the model to 0–30 cm, we used FAO–UNESCO data as summarized in Kern (1994) to develop a soil C distribution function for extrapolating down the profile to depth. Excluding organic soils (Histosols), the 0 to 10-cm soil layer represents, on average, 42.9 ± 2.2% of the SOC in the top 30 cm (Grace, Post, et al., 2006).

TABLE 1 Baseline and land management options as simulated by the SOCRATES soil C and ecosystem productivity model for assessing C sequestration strategies in the eastern Corn Belt of the United States

Baseline land type	Scenario A	Scenario B	Scenario C	Scenario D
Crop, prime				
Noneroded	Conventional tillage	Reduced tillage	No-tillage	n.a. ^a
Eroded	Conventional tillage	Reduced tillage	No-tillage	Pasture
Severely eroded	Forest	Pasture	—	—
Crop, marginal				
Noneroded	Forest	—	—	—
Eroded	Forest	—	—	—
Severely eroded	Forest	—	—	—
Pasture, prime	Pasture	—	—	—
Pasture, marginal				
Noneroded	Forest	—	—	—
Eroded	Forest	—	—	—
Severely eroded	Forest	—	—	—
Shrub	Shrub	—	—	—
Forest	Forest	—	—	—
Wetland	Wetlands	—	—	—
Mineland	Forest	Pasture	—	—
Urban	Urban	—	—	—
Other (water, etc.)	n.a.	n.a.	n.a.	n.a.

^an.a., not applicable.

Izaurre et al. (2001) found SOCRATES to be superior to both the CENTURY and RothC-26.3 models for predicting long-term changes in SOC in arable and rangeland soils of the Canadian prairies. SOCRATES has also been used to simulate changes in SOC across the North Central Region (NCR) of the United States (Grace, Colunga-Garcia, et al., 2006), which comprises the 12 states of the greater Midwest (North Dakota, South Dakota, Nebraska, Kansas, Minnesota, Iowa, Missouri, Wisconsin, Illinois, Michigan, Indiana, and Ohio). Actual data compilations of regional SOC stocks in the United States are rare; however, in the NCR study the SOCRATES estimate of 4,692 Tg for SOC stores (0–10 cm) is within 10% of an estimate derived by Franzmeier et al. (1985) from soil surveys specific to the NCR.

2.2 | Basic calculation unit and data inputs

We used the single STATSGO polygon map unit as the basic unit for computing the stocks of SOC (kg C m^{-2}). Two spatial data sets, the NLCD and the STATSGO soil maps, were intersected to delineate 16 land use types (including 10 condition specific types) within the ECB States (Table 1). First, we merged the 22 land classes of the NLCD into 10 categories:

cropland (including Fallow), pasture, shrub, forest, mineland, wetland, urban, urban grass, bare, and water. The areas of each of the 10 categories that fall within each STATSGO polygon map unit were then calculated.

Using STATSGO qualitative parameters, the pasture and cropland areas were then classified into prime or nonprime (marginal) farmlands, and then further subdivided based on their degree of erosion (defined in STATSGO as noneroded, eroded or severely eroded). Prime farmland refers to the land that has the soil quality, growing season, and water supply needed to produce sustained high crop yields (USDA–NRCS, 1995), whereas Marginal farmland is the land that is restricted by various soil physical–chemical properties, or environmental factors, for crop production (Nui & Duiker, 2006).

Each STATSGO polygon map unit represents a mapping unit ID. Each mapping unit ID is a unique combination of 1–21 soil taxon components. Average clay (%) and bulk density (g cm^{-3}) data were extracted from the STATSGO database for the 0-to-10-cm layer of each map unit. An annual precipitation (mm) and mean annual temperature ($^{\circ}\text{C}$) was assigned to each map unit within the region by overlaying an interpolated climate surface created by the PRISM climate mapping system (PRISM Climate Group, Oregon State University).

2.3 | Baseline soil organic C stocks

To develop baseline OC maps for the top 30 cm of soil, we used a similar methodology to that outlined in Grace, Colunga-Garcia, et al. (2006), based in part on the work of King et al. (1997). For all simulations, we ran the SOCRATES model within the Modeling Applications System Integrative Framework (Gage et al., 2001), a data handling and processing environment specifically developed to facilitate data-intensive regional-scale long-term simulations. Each STATSGO map unit was assigned a single dominant pre-agricultural vegetation type (forest, shrub, or grassland) drawn from the potential natural vegetation dataset of Kuchler (1993). We developed a pre-agriculture SOC map for the region by running the SOCRATES model under the respective land uses (with full litter return) until an equilibrium state of SOC was maintained in all map units (approximately 3,000 yr).

The respective masses (kg C m^{-2}) of OC in the plant and soil pools (i.e., decomposable plant material, resistant plant material, microbial biomass, and humus) of SOCRATES in each map unit for the year 1850 served as initialization values for the post-agriculture simulations required to develop a late 1990s SOC surface for the ECB. As a polygon-specific NPP calculation is the basis for C inputs into the soil, we made a number of assumptions to mimic agronomic practice and productivity between 1850 and the end of the 20th century. For cropland (prime or marginal) under conventional tillage, we used the same procedure as outlined in Grace, Colunga-Garcia, et al. (2006) and gradually increased annual crop residue retention over the century from 5 to 35% of NPP.

To account for increases in productivity in the Midwest since the 1950s with the introduction of improved genetics, fertilizer, pest management, and equipment (Cao et al., 2018; Hatfield et al., 2018), an NPP modifier of 1.4 was introduced in the latter decades of the 1900s. This modifier is equivalent to the incremental increase in corn and soybean yields in the ECB between 1960 and 2000 as reported by the U.S. National Agricultural Statistics Service. The adoption of conservation tillage practices in the ECB has been historically low; for example, only 23% of the area under corn–soybean (in Indiana, Michigan, and Ohio) during the 1990s was no-till as reported by the Conservation Tillage Information Center through its Crop Residue Management Survey. In addition, only half of the area reported for the United States would qualify as permanent no-till (Derpsch et al., 2010).

In noneroded prime cropland and pasture, NPP was assumed to be unconstrained (i.e., 100% of potential as determined by temperature or precipitation and fertilizer inputs). For eroded lands, NPP was constrained to 90%, whereas for severely eroded and marginal lands, the NPP was constrained to 65% of potential. These reduction factors were based on multiple location by year observations across the

Midwest (Battiston et al., 1987; Mokma & Sietz, 1992; Olson & Carmer, 1990; Schertz et al., 1989). Impacts of erosion and farmland suitability were considered multiplicative; for example, marginal severely eroded lands would perform at only 42% of potential NPP. For mineland and urban land types, we assumed zero or negligible NPP.

The specific association of the SOC concentration (kg m^{-2}) with each of the STATSGO soil–NLCD land use intersections within a polygon can then provide the basis for summation of total SOC within a soil–land use category, a map unit, a state, or the entire region. For example, to develop a total SOC budget for each map unit, we used a summation procedure:

$$\text{TSOCP}_k = \text{SOCP} \cdot \text{LUP}_k \cdot \text{POLYAREA} \quad (1)$$

where TSOCP_k is the total SOC pool in polygon map unit k (kg), SOCP is the total SOC pool to 30-cm depth estimated by SOCRATES (kg m^{-2}) for STATSGO soil–NLCD land use category k , LUP_k is the portion of the area of the polygon unit represented by STATSGO–NLCD land use category k , and POLYAREA is the total area of the polygon map unit (m^2).

2.4 | Land use and management impacts

A 20-yr time frame consistent with existing good practice guidelines (Eggleston et al., 2006) was chosen for the simulations to assess the potential impact of management practices and land use change on SOC stocks (0–30 cm). The average climatic conditions within the region were deemed not to have significantly changed during this time period. Bulk density was also left unchanged from the original value extracted from STATSGO as the majority of evidence from replicated long-term tillage trials (Mishra et al., 2010; Syswerda et al., 2011) and unreplicated paired-site comparisons (Blanco-Canqui & Lal, 2008; Chatterjee & Lal, 2009; Christopher et al., 2009) across the region show no consistent change in bulk density over time.

Potential changes in topsoil OC for the 15 respective terrestrial land use types were simulated in response to improved management or land use change strategies outlined in Table 1. The respective mass of SOC in the decomposable plant material, resistant plant material, microbial biomass, and humus pools (kg C m^{-2}) of SOCRATES for each land use within each map unit at the conclusion of the baseline simulation for the year 2000 served as initialization values for the future management simulations.

Site-specific NPP calculations were the basis for C inputs into the soil. For reduced and no-tillage strategies, residue returns were specified as 45 and 65% respectively (Grace, Colunga-Garcia, et al., 2006) with yields remaining the same as conventional tillage practices (DeFelice et al., 2006;

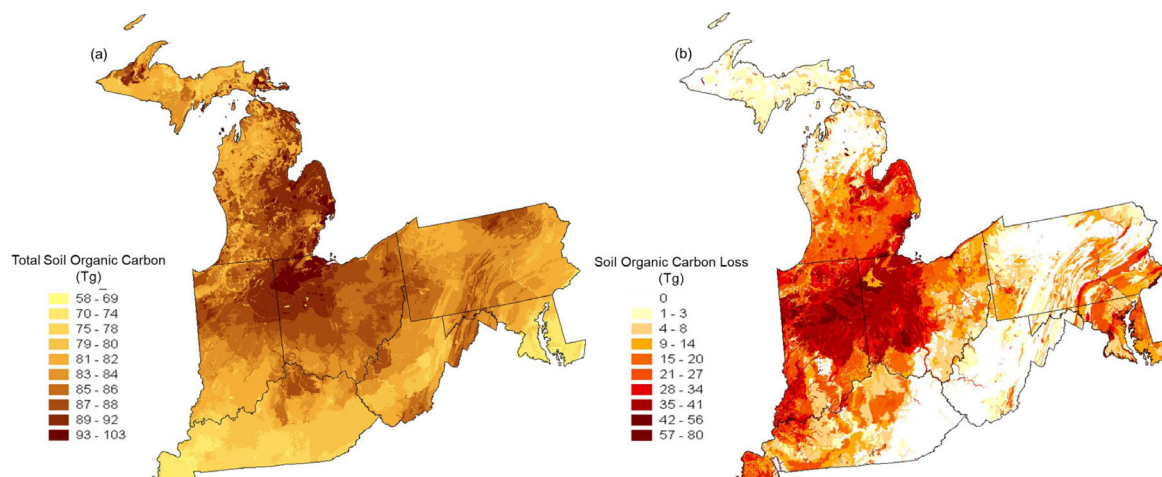


FIGURE 1 (a) Pre-agriculture soil organic C stocks (0–30 cm) and (b) loss of soil organic C by the end of the 20th century in response to agricultural practices across the eastern Corn Belt of the United States as simulated by SOCRATES.

Pittelkow et al., 2015). The first order decay constant for the stable SOC pool in SOCRATES (originally calibrated on conventional tillage systems) was decreased by 2.5 and 10% for reduced and no-tillage practices, respectively. The decrease in decay rate under no-tillage has been calibrated based on the average per annum change in SOC of 90 g m^{-2} (0–23 cm) in long-term no-till corn–soybean rotations reported in the meta-analysis of West and Post (2002), with 85% of this change in the top 7 cm. The reductions in decay constant are highly conservative compared with the model described in Clay et al. (2012), who reduced native SOC decomposition by 40 and 60% for reduced and no-tillage strategies, respectively.

Specific land use areas were assumed not to have changed relative to the NLCD dataset; however, when imposing a new land use or agronomic strategy, the previous land condition (erosion class and farmland suitability) was deemed to still be in effect when calculating NPP. For example, a shift to forestry on conventionally tilled severely eroded prime cropland would still be constrained at 65% of NPP for the 20-yr simulation. Whereas increases in SOC are known to promote improved soil physical and chemical health, it is beyond the scope of this study to include these assumptions.

3 | RESULTS AND DISCUSSION

3.1 | Land areas

The respective areas of the 15 land use types for the 7,669 STATSGO polygon map units in the ECB region are shown on a per state basis in Table 2. Forests occupy >47% of the land area of the region, with cropland and pasture comprising 23 and 17%, respectively. Over 84% of cropland is in the states of Indiana, Michigan, and Ohio, and over 70% of cropland is considered noneroded prime farmland.

3.2 | Pre-agriculture and baseline SOC stocks

The pre-agriculture SOC map of the ECB (Figure 1a) is based on the long-term decomposition of litter and roots under its natural pre-agricultural vegetation, primarily forest. We estimate an OC stock of 5,507 Tg in the top 30 cm of the ECB prior to the introduction of agricultural practices in the mid-1800s (Table 3).

Widespread and rapid introduction of agrarian practices and subsequent land use changes across the ECB since 1850 reduced SOC stocks by 15.5% to 4,658 Tg by the end of the 20th century (Figure 1b). The store of SOC (0–30 cm) in cropland (prime and marginal) is 632 Tg C (or 41 Mg C ha^{-1} ; Table 4), having declined from the initial pre-agricultural state of 1,305 Tg C (or 85 Mg C ha^{-1}). This 52% decrease in SOC in response to long-term conventional cropping is consistent with many field observations (e.g., Lal et al., 2002; Sanderman et al., 2017; Syswerda et al., 2011). Using STATSGO data, Tan et al. (2006) estimated a SOC concentration (0–30 cm) of 64 Mg C ha^{-1} for cropland in this region, but did not take into account land condition. Soil OC data associated with the STATSGO map units are also not land use specific, unlike our model estimates. Our modeling using the STATSGO database identified 30% of the cropland in a more degraded state than noneroded prime farmland, which reduced NPP and C inputs and subsequent SOC storage.

3.3 | Land management impacts on SOC stocks

SOCRATES simulations show that after 20 yr of no-tillage, the OC stock in prime cropland soils (0–30 cm) in the ECB would increase (on average) by $11.9 \text{ Mg C ha}^{-1}$ (equivalent

TABLE 2 Summary of areas by state for the land use types generated by the intersection of the National Land Cover Database and the State Soil Geographic database for the eastern Corn Belt of the United States

Category	Condition	IN	KY	MD	MI	OH	PA	WV	Total
kha									
Mineland		22	52	29	68	26	125	73	396
Forest		1,763	6,230	1,059	6,170	3,361	7,644	5,239	31,465
Shrub		38	0	0	319	0	0	0	357
Pasture ^a		1,771	2,147	632	1,371	2,315	2,644	689	11,570
Prime cropland	Noneroded	3,362	1,010	289	2,611	3,047	370	47	10,736
	Eroded	933	39	0	80	513	0	0	1,565
	Severely eroded	25	0	0	1	2	0	0	29
Marginal cropland	Noneroded	559	293	63	910	410	211	71	2,517
	Eroded	231	40	0	0	101	0	0	372
	Severely eroded	30	27	1	0	11	0	0	69
Wetland		164	182	221	2,558	149	98	15	3,389
Urban		370	246	216	540	624	504	83	2,583
Other (including water) ^b		109	195	246	442	122	135	54	1,303
Total		9,377	10,461	2,756	15,070	10,681	11,731	6,271	66,347

^aIncludes all pastures (prime and marginal, all classes of erosion).

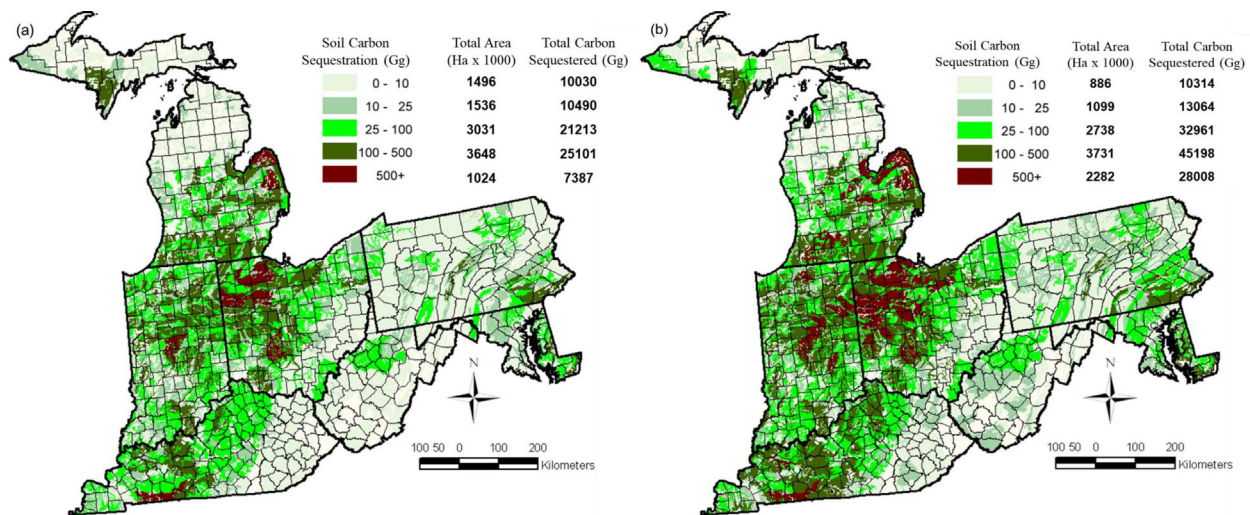
^bWater = 1,260 kha and remainder is barren or "land not accounted for" excluding Great Lakes.

TABLE 3 Pre-agriculture soil organic C stores (0–30 cm) for the eastern Corn Belt of the United States

Category	IN	KY	MD	MI	OH	PA	WV	Total
Tg								
Forest	145.4	492.3	82.8	514.0	287.4	635.3	429.6	2,586.8
Shrub	3.2	0.0	0.0	26.6	0.0	0.0	0.0	29.8
Pasture	147.2	168.1	49.9	118.7	199.2	221.0	57.3	961.4
Cropland	436.6	109.3	26.8	314.4	360.5	48.5	0.1	1,296.2
Other ^a	55.3	50.7	51.4	298.7	78.7	70.7	18.0	623.5
Total	787.7	820.4	210.9	1,272.4	925.9	975.5	514.6	5,507.4

Note: Land use categories as generated by the intersection of the National Land Cover Database and the State Soil Geographic database.

^aIncludes mineland, wetland, urban, and water.

**FIGURE 2** Soil organic C sequestration potential (0–30 cm) of (a) reduced and (b) no-till practices after 20 yr on prime noneroded cropland in the eastern Corn Belt of the United States as simulated by SOCRATES.

to 0.6 Mg C ha⁻¹ yr⁻¹). This additional 147 Tg C (Table 5) is comparable to the 136 Tg C sequestration estimate of Tan et al. (2006) after 20 yr of no-tillage. Mishra et al. (2012) used the empirical IPCC Tier 2 C inventory approach (Eggleston et al., 2006) and estimated that 235 Tg C would be sequestered over 20 yr under no-tillage, but that assessment did not take into account cropland condition, and does not explicitly take into account NPP and climate. Our estimate of net C sequestration under no-tillage would be 181 Tg C (14.7 Mg C ha⁻¹ or 0.73 Mg C ha⁻¹ yr⁻¹) considering that conventional tillage over 20 yr would have mined 35 Tg C. If we consider the average top-soil bulk density for the ECB of 1.26 g cm⁻³, a net C sequestration of 14.7 Mg C ha⁻¹ over 20 yr under no-tillage equates to a potential increase of 0.4% SOC in the top 30 cm of soils under crop. This is far short of the “aspirational” 0.4% SOC increase per annum promoted by the “4 per 1000” initiative.

The imposition of reduced and no-tillage on noneroded prime cropland would provide 160 Tg C and 104 Tg C, respectively. The regions providing the greatest returns with reduced and no-tillage technologies on noneroded prime crop-

land are western Ohio (particularly the northwest), central Indiana, southern Michigan (adjacent to Saginaw Bay), and southern Kentucky (Figures 2a,b). Southern Kentucky provides some of the largest returns through no-tillage on a per area basis, up to 0.82 Mg C ha⁻¹ yr⁻¹, although the areal extent of noneroded prime cropland is significantly less than in other regions. Sequestration hotspots (>500 Gg increase in SOC) under no-tillage cover approximately 2.3 Mha and would potentially provide 28 Tg C over 20 yr (Figure 2b).

Reduced and no-tillage management options on eroded prime cropland would provide SOC returns for the region of 9.5–16.9 Tg over 20 yr (Table 5). There is extensive eroded prime cropland in southern and northeastern Indiana, as well as in western Ohio, which responds favorably to reduced and no-tillage practices (Figures 3a,b). Sequestration hotspots (>150 Gg increase in SOC) under no-tillage cover approximately 0.65 Mha and could potentially sequester 6.9 Tg C over 20 yr. The introduction of pastures on these soils provides returns in OC much the same as reduced tillage (data not shown). The lack of eroded and severely eroded prime

T A B L E 4 Baseline soil organic C stores (0–30 cm) at the end of the 20th century simulated by SOCRATES for land use types generated by the intersection of the National Land Cover Database and the State Soil Geographic database for the eastern Corn Belt of the United States

Category	Condition	IN	KY	MD	MI	T _g				WV	Total
						OH	PA				
Mineland		0.6	1.2	0.7	2.9	0.9	4.3			2.2	12.7
Forest		159.6	543.6	91.0	551.4	313.8	690.7			470.4	2,820.5
Shrub		3.3	0.0	0.0	27.6	0.0	0.0			0.0	30.9
Pasture ^a		136.6	152.8	45.8	112.5	184.8	202.2			49.5	884.0
Prime cropland											
	Noneroded	137.1	31.4	9.1	124.2	132.7	15.0			1.8	451.3
	Eroded	37.2	1.1	0.0	3.5	21.4	0.0			0.0	63.2
	Severely eroded	0.9	0.0	0.0	0.1	0.1	0.0			0.0	1.0
Marginal cropland											
	Noneroded	21.6	9.2	2.1	41.6	17.3	8.4			2.7	102.7
	Eroded	7.7	1.2	0.0	0.0	3.6	0.0			0.0	12.5
	Severely eroded	0.9	0.6	0.0	0.0	0.4	0.0			0.0	1.8
Wetland											
		13.75	13.8	13.9	16.0	211.8	12.9			8.1	277.6
Urban		n.a. ^b	n.a.	n.a.	n.a.	n.a.	n.a.			n.a.	n.a.
Other (including water)		n.a.	n.a.	n.a.	n.a.	n.a.	n.a.			n.a.	n.a.
Total		519.0	754.9	164.8	1,075.5	687.8	928.5			527.8	4,658.2

^aIncludes all pastures (prime and marginal, all classes of erosion).
^bn.a., not applicable.

TABLE 5 Potential changes in soil organic C (0–30 cm) and, where applicable, aboveground forest biomass estimated by the SOCRATES soil C and ecosystem productivity simulation model for the eastern Corn Belt of the United States after 20 yr of land use and management change

Category	Condition	Tg C	IN	KY	MD	MI	OH	PA	WV	Total
Mineland	Pasture		0.23	0.56	0.28	0.40	0.24	1.06	0.68	3.45
	Forest soil		0.27	0.66	0.33	0.48	0.29	1.28	0.81	4.13
	Forest (soil + biomass)		2.98	7.45	3.88	5.84	3.16	13.95	8.94	46.20
Prime cropland	No-tillage		41.53	13.99	3.69	27.52	37.88	4.36	0.58	129.55
	No-tillage (net) ^a		50.96	16.40	4.38	35.05	46.76	5.37	0.71	159.64
	Reduced tillage		23.87	8.30	2.17	15.36	21.69	2.49	0.34	74.22
	Reduced tillage (net)		33.30	10.72	2.86	22.89	30.57	3.51	0.46	104.32
	Conventional tillage		-9.43	-2.42	-0.69	-7.54	-8.88	-1.02	-0.13	-30.10
Eroded	No-tillage		10.10	0.48	0.00	0.78	5.58	0.00	0.00	16.94
	No-tillage (net) ^a		12.78	0.57	0.00	1.01	7.11	0.00	0.00	21.47
	Reduced tillage		5.66	0.28	0.00	0.42	3.12	0.00	0.00	9.48
	Reduced tillage (net)		8.34	0.37	0.00	0.66	4.64	0.00	0.00	14.01
Severely eroded	Conventional tillage		-2.69	-0.09	0.00	-0.23	-1.52	0.00	0.00	-4.53
	Pasture		0.11	0.00	0.00	0.00	0.01	0.00	0.00	0.12
	Forest soil		0.14	0.00	0.00	0.01	0.01	0.00	0.00	0.16
	Forest (soil + biomass)		1.40	0.00	0.00	0.06	0.12	0.00	0.00	1.58
	Forest soil		3.29	1.86	0.31	2.83	2.26	0.90	0.33	11.77
Marginal cropland ^b	Forest (soil + biomass)		37.83	19.84	3.62	37.99	24.46	10.40	3.66	137.80
Marginal pasture ^b	Forest soil		0.59	0.30	0.02	-0.06	0.22	-0.04	0.01	1.04
	Forest (soil + biomass)		29.62	53.23	23.97	30.20	40.13	53.53	22.68	253.35

^aNet sequestration after correcting for conventional tillage losses over 20 yr.

^bMarginal (nonprime) farmland and all erosion classes.

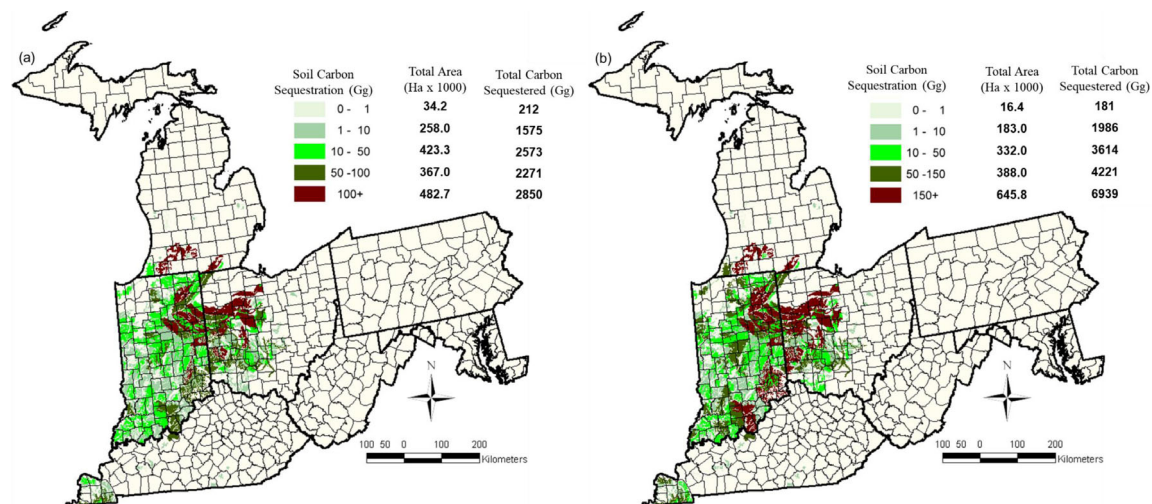


FIGURE 3 Soil organic C sequestration potential (0–30 cm) of (a) reduced and (b) no-till practices after 20 yr on eroded prime cropland in the eastern Corn Belt of the United States as simulated by SOCRATES.

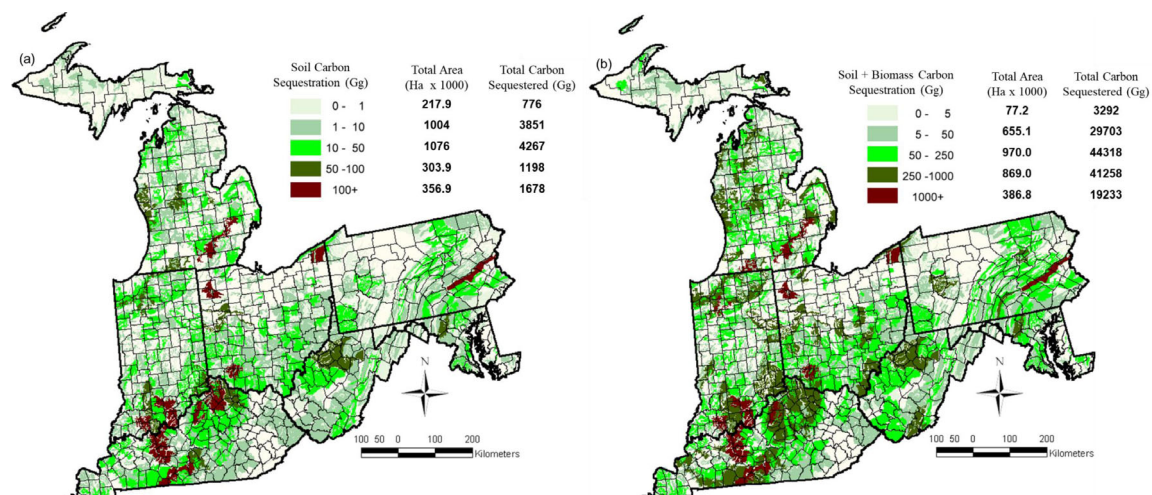


FIGURE 4 Carbon sequestration potential of (a) soil (0–30 cm), and (b) soil and biomass after 20 yr on conversion of marginal cropland (all erosion classes) to forestry in the eastern Corn Belt of the United States as simulated by SOCRATES.

cropland in other states (compared with Indiana and Ohio) suggests some degree of subjectivity in the classification of these erosion classes across the region.

Forests offer slightly greater SOC returns compared with pasture on severely eroded prime cropland (Table 5). One particular hotspot of over 6,000 ha in western Indiana would provide a terrestrial C sink (soil and aboveground biomass) of over 338 Gg C over 20 yr under forestry. Model simulations also suggest that the conversion of marginal cropland to forest could return up to 0.2 Mg C ha⁻¹ yr⁻¹ in SOC, with overall gains (soil and aboveground forest biomass) in excess of 46 Mg C ha⁻¹ over 20 yr (Figures 4a,b). Relatively large sequestration hot spots, accumulating 2.3–3.9 Tg C over 20 yr, can be found in southern Michigan and northwest Ohio. Other hot spots occur in northern Kentucky and southern Indiana.

Marginal pasture converted to forest offers little gain in SOC but would yield as much as 114 Mg C ha⁻¹ in aboveground forest biomass over 20 yr (data not shown). The conversion of marginal cropland and pasture to forest would yield an additional 394 Tg of terrestrial C, of which only 3.2% would be attributed to increases in the SOC pool over 20 yr (Table 4). Indiana, Kentucky, and Pennsylvania would provide the largest overall returns in C (Figures 5a,b). Sequestration hotspots (>2 Tg increase in terrestrial C) cover 1.4 Mha and could potentially return 75 Tg C over 20 yr.

The conversion of mineland to forest would return in excess of 15 Mg C ha⁻¹ over 20 yr in SOC throughout Kentucky and northwest Ohio; however, land areas are quite small. Western Kentucky, many parts of West Virginia, and a narrow ridge through central Pennsylvania provide some of the highest estimations of terrestrial C return of all management strategies,

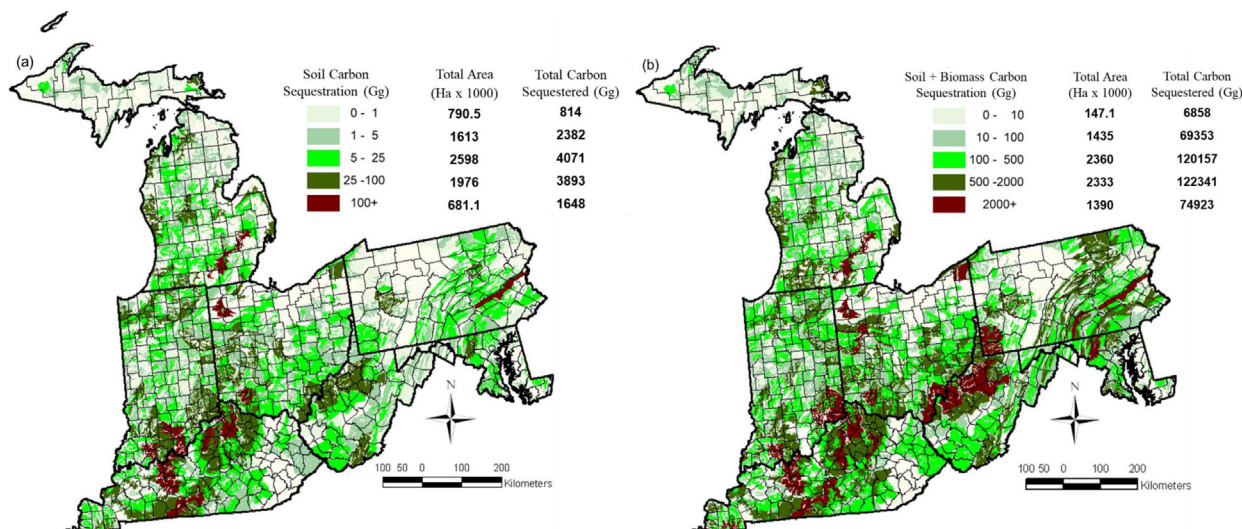


FIGURE 5 Carbon sequestration potential of (a) soil (0–30 cm), and (b) soil and biomass after 20 yr on conversion of marginal cropland and pasture to forestry in the eastern Corn Belt of the United States as simulated by SOCRATES.

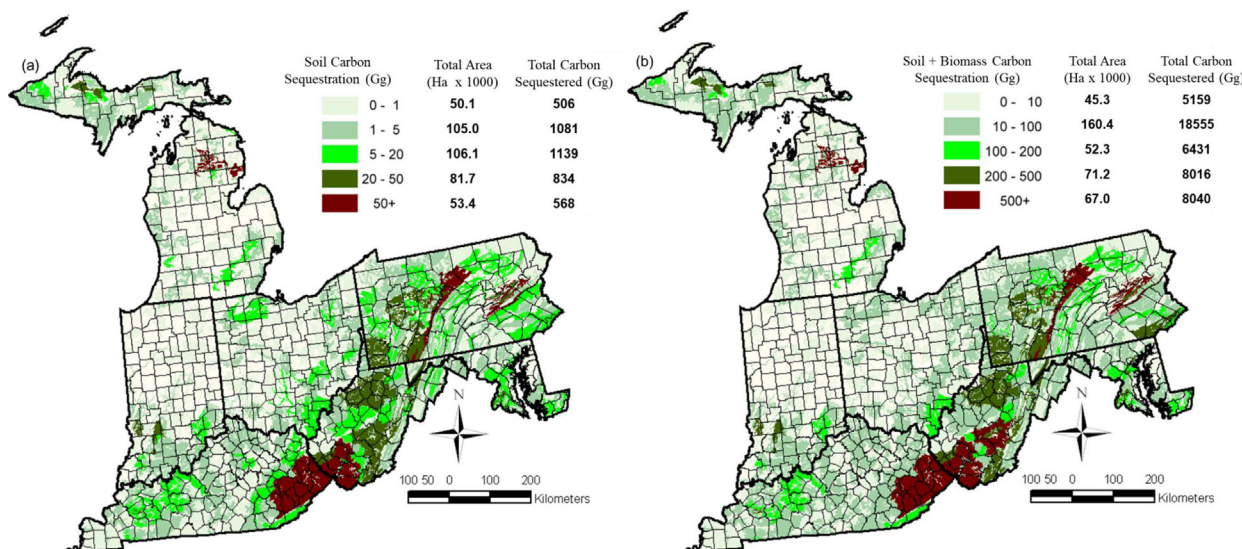


FIGURE 6 Carbon sequestration potential of (a) soil (0–30 cm), and (b) soil and biomass after 20 yr on conversion of minelands to forestry in the eastern Corn Belt of the United States as simulated by SOCRATES.

in excess of 154 Mg C ha^{-1} over 20 yr (Figures 6a,b). Potential hotspots returning in excess of 1 Tg in soil and biomass C (combined) have been identified in eastern Kentucky and into West Virginia, as well as in central Pennsylvania. The potential of pastures or other herbaceous perennial crops such as biofuels to improve SOC on mineland is slightly less than the forest management strategy.

3.4 | Assumptions and recommendations

Simulation modeling is a valuable tool for rapidly assessing management scenarios across both space and time, as well as a means for identifying critical gaps in knowledge. Here

we assessed the influence of land condition, land use management, and change on SOC in a geographic region in both time and space. This is not possible using the STATSGO and NLCD databases in isolation, as the SOC database does not relate to a specific land use or condition on a one to one basis. Nevertheless, there are a number of assumptions in our analysis that prompt recommendations for improving future modeling assessments in the region.

First, there is a lack of high quality replicated long-term field trials in the ECB that include SOC sequestration practices. Any simulation model is only as good as the underlying data used in calibration and validation. Apart from the Long Term Ecological Research site at the W.K. Kellogg Biological Station (Syswerda et al., 2011) and multiple trials in

Ohio (Dick et al., 1997), many of the long-term trials that exist in the U.S. Midwest (e.g., Sanborn, Morrow, Arlington, and Lancaster) compare antiquated agronomic practices (e.g., Miles & Brown, 2011; Nafziger & Dunker, 2011; Vanotti et al., 1997). The latter, while useful for process understanding of SOC dynamics, do not include conservation tillage strategies. Additional resources are required to supplement existing trials and target tillage and cover crop options; perhaps, for example, augmentation of the Long Term Agricultural Research network (Kleinman, et al., 2018). These research trials could ideally be located on east–west and north–south transects across the region to both ensure that different climatic conditions are adequately covered, and that the efficacy of subregional management strategies can be determined. Well-documented and managed research trials are critical for calibrating simulation models.

Second, the identification and preservation of georeferenced long-term sites across the region with known land use histories (which fit the current categories) and well-documented changes (with data) are needed. These sites should be located across soil types and states, and thus provide a diverse dataset for validation of simulation models. On-farm data provides a more realistic data source but does require quality control and regular soil sampling to augment past information in developing time series. However, without the advantage of fully replicated trials, there is high risk of inconsistency with respect to land management impacts on SOC stocks (e.g., Blanco-Canqui & Lal, 2008; Christopher et al., 2009). The development of a comprehensive on-farm network of C assessment trials would ensure that long-term trial data is further consolidated within each state. This “satellite” network could concentrate on hot-spot locations as identified in this study. The network would also form the basis of extending practices throughout the region and developing county or watershed-based C trading groups.

Third, the alignment of soil data from the STATSGO database with specific land use categories and conditions to ensure a more accurate map of SOC stores should be generated. The magnitude of SOC sequestration potential over time is dependent on the original state, whether it be calculated from a database or derived from a model. Access to georeferenced soil data from within the STATSGO or similar databases may facilitate this alignment and reassessment. Native forests and pasture–grassland data is of particular interest in order to ensure an accurate pre-agricultural SOC estimate, as this lays the platform for subsequent C changes.

Fourth, there is a need to accommodate future land use changes scenarios in an overall assessment. This is critical for assessing the impact of population growth and climate change on agricultural land use. Temporal land use change must be incorporated into the analysis. Algorithms exist to accommodate these changes into our modeling framework.

Finally, there is a need to include non-CO₂ greenhouse gases in the predictive framework. Although we have focused on SOC change in this assessment, the UNFCCC specifically requires full cost C accounting in all inventories so that global warming potential of a particular management can be fully assessed. This increases data assimilation tasks by an order of magnitude, but full cost studies (e.g., Gelfand et al., 2013; Grace, et al., 2003, 2010, 2012; Mosier, et al., 2005; Robertson & Grace, 2004; Robertson, et al., 2000) have shown that the mitigation benefits of SOC sequestration through tillage management or conversion to pasture can be negated by other management practices (e.g., nitrous oxide from increased N fertilizer inputs or methane from livestock), and full cost analyses provide the necessary systems-level integration to fully understand total mitigation impacts.

4 | CONCLUSIONS

Our assessment of SOC changes in the ECB is unique in combining both land use and condition to provide realistic estimates of the potential impact of management or land use change. Our modeled estimate of SOC stocks across multiple land uses at the end of the 20th century is 4,658 Tg C, 15.5% less than the pre-agriculture stock of SOC for the ECB. Soil OC stocks in the 15.3 Mha of cropland in the ECB are estimated to be 632 Tg, having declined by just over 50% since the introduction of agriculture. Complete adoption of no-tillage on prime cropland would potentially yield 146 Tg of SOC over 20 yr, which is 181 Tg C more than conventional tillage over the same time period. The conversion of marginal (nonprime) agricultural lands to forest or pasture or perennial biofuel crops such as switchgrass or short-rotation poplar would yield at least 13 Tg additional SOC and, if forest, 381 Tg C in aboveground biomass. The rehabilitation of mineland would likely yield an additional 4 Tg in SOC and 42 Tg C in biomass. Whereas potential increases in SOC in the ECB via conservation tillage are far from the magnitude promoted by the “4 per 1000” initiative, there is no doubt that small continuous increases in SOC provide multiple benefits with respect to soil health, productivity, and the sustainability of farming systems.

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AUTHOR CONTRIBUTIONS

Peter Grace, Conceptualisation, Methodology, Formal analysis, Writing-original draft, Writing review & editing; G. Philip Robertson, Funding acquisition, Conceptualization, Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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