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Limited potential for terrestrial carbon sequestration to offset fossil-fuel emissions in the upper midwestern US

Cinzia Fissore[1,*], Javier Espeleta[1,2], Edward A Nater[1], Sarah E Hobbie[3], and Peter B Reich[4]

Many carbon dioxide (CO_2) emission-reduction strategies currently under consideration rely on terrestrial carbon (C) sequestration to offset substantial proportions of CO_2 emissions. We estimated C sequestration rates and potential land areas for a diverse array of land-cover changes in the Upper Midwest of the US, a "best case" region for this study because of its relatively modest CO_2 emissions and the large areas of cropland potentially available for conversion. We then developed scenarios that apply some of the most widespread mitigation strategies to the region: the first, which aimed to offset 29% of regional CO_2 emissions, required the unrealistic loss of two-thirds of working cropland; the second, which estimated the emission offset attainable by conversion of 10% of harvested croplands (5.8% of the US total), resulted in < 5% CO_2 emissions reduction for the region (< 1.1% of total US emissions). There is limited capacity for terrestrial C sequestration, so strategies should aim to directly reduce CO_2 emissions to mitigate rising atmospheric CO_2 concentrations.

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Societal concern over global warming and its link to increasing atmospheric carbon dioxide (CO_2) concentrations has motivated many local communities, states, and countries to develop plans to reduce net fluxes of CO_2 to the atmosphere. These plans involve two general strategies: (1) direct reduction of fossil-fuel-based CO_2 emissions through enhanced energy conservation and efficiency and development of alternative energy sources; or (2) sequestration of atmospheric carbon (C) in standing biomass or C-depleted agricultural soils through changes in land cover or management practices, such as the conversion of annual row crops to perennial vegetation (forest or grassland) or adoption of agricultural practices, such as conservation tillage, that are thought to promote net C storage (Paustian *et al.* 1998; Six *et al.* 2002; Niu and Duiker 2006).

The Intergovernmental Panel on Climate Change (IPCC 2007), among others, points to afforestation and other changes in land use as potential ways to offset part of current CO_2 emissions worldwide. Mitigation plans drafted by several US states also rely on terrestrial C sequestration for a large proportion, or even the majority of net CO_2 flux reductions. For example, the Minnesota Climate Change Advisory Group (MNCCAG 2008) proposes that terrestrial C sequestration will account for 38% of Minnesota's projected 2025 C emission-reductions strategy; the Montana Climate Change Action Plan (2007) proposes to offset 11% of its C emissions by terrestrial sequestration, by 2020; and the Idaho Soil Conservation Commission (2003) proposes that Idaho's fossil-fuel emissions can be offset almost entirely by changes in management practices and land cover.

While efforts to mitigate C emissions are needed, it is questionable whether terrestrial C sequestration can achieve such ambitious results, particularly in light of (1) the impacts of local strategies on the global food production system; (2) increasing pressures on agricultural lands from an array of competing sectors, including food and biofuel production and urbanization; and (3) burgeoning evidence that previously published rates of C sequestration attributed to the conversion from conventional tillage to no-till systems were overly optimistic. In fact, C sequestration rates may not differ substantially between alternative tillage practices (Baker *et al.* 2007; Blanco-Canqui and Lal 2008).

The purpose of this study was to provide a conservative estimate of the potential magnitude of CO_2 emissions that could be offset by terrestrial C sequestration in the Upper Midwest of the US. For our analysis, we chose assumptions and situations that produced the most optimistic (ie largest) estimates of potential C sequestration, to ensure that we did not underestimate the magnitude of potential offsets. These included no reversal of land to previous land-cover type or management practice with low C stocks (eg croplands), no loss of C accrued in standing biomass by fire, disease, or insect invasion, no saturation of soil-C storage capacity, and no "leakage", whereby high C-stock lands outside the Upper Midwest (eg tropical forests) are converted to land uses that have lower C stocks (eg croplands) to counter losses of agricultural productivity resulting from our scenario conversions. The resulting estimates represent a reasonable maximum of potential CO_2 emission offsets due to C sequestration for the region.

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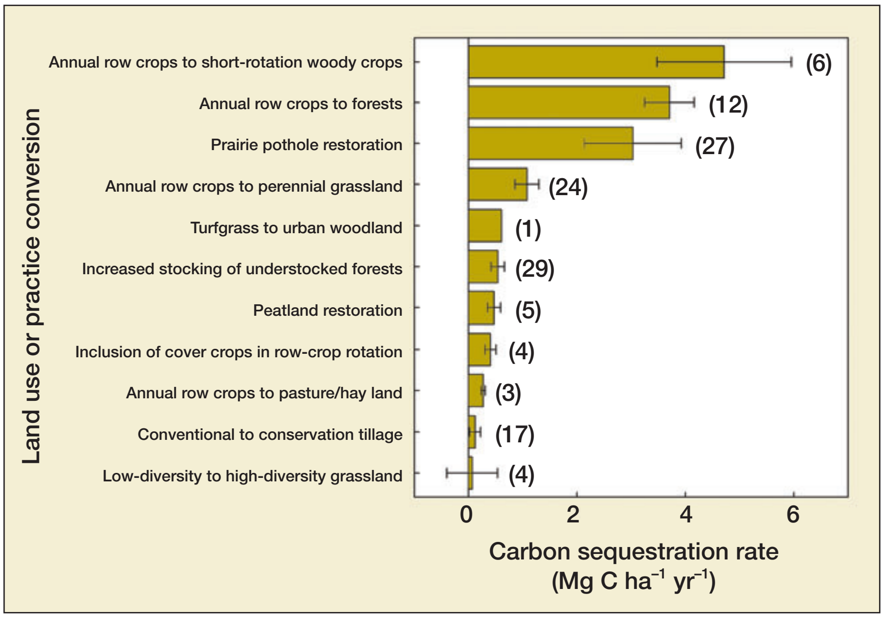

Figure 1. *Estimated C sequestration rates (Mg C ha^{-1} yr^{-1}) associated with land-cover or land-management changes in the Upper Midwest of the US (see WebPanel 1). Estimates were obtained from published empirical studies for the Upper Midwest and other ecologically comparable locations. Carbon sequestration rates apply to a 50-year timeframe, with the exception of short-rotation woody crops, for which net C sequestration rate corresponds to the rotation time (harvest cycle of approximately 20 years) without accounting for the fate of harvested products or other C losses that would occur upon harvest. Bars are means ± standard error; numbers in parentheses indicate number of observations.*

This conservative estimate is developed in two contrasting land-cover and management-change scenarios (see WebPanel 1) that are based on mean C sequestration rates, calculated from a critical review of published empirical C sequestration values appropriate for the region. We deliberately excluded more complex models of land-cover and management changes in our analyses, because the added degree of refinement was unnecessary for the estimate we sought to develop. Existing estimates of regional emission-offset potentials either focused on very different ecological areas (eg Freibauer *et al.* 2004) or explored few land-use-change options, often relying on model results and assumptions of high C sequestration rates associated with reduced tillage practices (Freibauer *et al.* 2004; Jackson and Schlesinger 2004).

Methods

We selected the Upper Midwest of the US for our study region because it represents a "best case" scenario for the potential for C sequestration to offset greenhouse-gas (GHG) emissions. The geographic area considered (Indiana, Illinois, Iowa, Kansas, Michigan, Minnesota, North Dakota, Nebraska, Ohio, South Dakota, and Wisconsin) is a good test case for several reasons. First, it is characterized by a moderate (by US standards) C economy (378 Tg C yr^{-1}); second, it covers a large area (1 770 000 km^2), roughly comparable to the combined areas of France, Germany, Spain, and Italy; and finally, it is used intensively for agriculture, with nearly 73% of the land area being farmed (NASS 2002). Relative to the entire US, the Upper Midwest has approximately 23% of C emissions from fossil fuels, 19% of the total land area, 20% of the population, and 58% of the harvested cropland (annual crops: mainly corn, soybeans, and wheat; NASS 2002).

Because cultivated agricultural lands are often C-depleted, they have the potential to sequester C when converted to land-cover types that positively affect their net C balance. The potential for terrestrial C sequestration to offset current C emissions in the Upper Midwest region is high, resulting from the large proportion of harvested croplands relative to emissions. Prior to European settlement, the Upper Midwest was largely covered by vegetation types (forests, prairies, and wetlands) with high C stocks in standing plant biomass, peat, or soil organic matter. A large proportion of this area was converted into cropland (much of it artificially drained), with a corresponding reduction in biomass and, over time, soil-C stocks. The reversion of harvested croplands to these former (or structurally similar) land types should produce net C sequestration.

We used published data applicable to the region to derive mean C sequestration rates for the most common land-cover and management changes proposed, and applied these rates to two hypothetical CO_2 emission-reduction scenarios to estimate the terrestrial C sequestration potential for the region. Scenario 1 involves afforestation and restoration of perennial grassland as well as restoring prairie pothole wetlands, where ecologically feasible, and stocking all understocked forests in each state to achieve a total of 29% CO_2 emission offsets for the entire region (sensu Pacala and Socolow 2004). Scenario 2 involves the conversion of 10% of land currently used for agriculture into a combination of the practices stated above, to estimate the resulting CO_2 emission reduction (see WebPanel 1).

Results and discussion

Mean C sequestration rates for different land-cover and management changes varied between 0.06 and 4.7 Mg C ha^{-1} yr^{-1}, with the highest rates (Figure 1) associated with the conversion of annual row-crop agricultural lands to short-rotation woody crops (4.7 Mg C ha^{-1} yr^{-1} before harvest), forest (3.7 Mg C ha^{-1} yr^{-1}), and restored prairie pothole wetlands (3.1 Mg C ha^{-1} yr^{-1}). Conversion from cropland to forest achieved the highest rate of C sequestration during the 50-year projected timeframe of this study because of major C accumulation in standing biomass (Liski *et al.* 2002). The introduction of hybrid or other fast-growing tree species as short-rotation woody crops produces even higher terrestrial C sequestration rates over shorter timeframes (ie over the course of the crop rotation, typically less than 20 years), but a full C lifecycle analysis of the fate of harvested woody products is necessary to project this sequestration estimate over time periods longer than a single rotation. Major soil-C sequestration rates are also associated with restored perennial grasslands (Tilman *et al.* 2001; McLauchlan *et al.* 2006).

The mean C sequestration rates of a number of other widely proposed land-cover and management changes are much more modest (between 0.1 and 0.6 Mg C ha^{-1} yr^{-1}; Figure 1), and for some of these practices, namely conversion from low- to high-diversity grassland and from conventional to conservation tillage, the variability is so great relative to the mean that one cannot determine whether net C sequestration actually occurs (Figure 1). In particular, C sequestration rates associated with the conversion from conventional to conservation tillage reported in 17 studies across the Upper Midwest were both negligible (mean = 0.1 Mg C ha^{-1} yr^{-1}) and highly variable (ranging from –0.8 to 0.8 Mg C ha^{-1} yr^{-1}). Recent studies indicate that conservation tillage is more likely to cause a redistribution of C within the soil profile than an overall accrual (Baker *et al.* 2007; Blanco-Canqui and Lal 2008).

Using these C sequestration rates (Figure 1; WebPanel 1), we elaborated two scenarios. Scenario 1 is based on the widely cited work of Pacala and Socolow (2004), whereas Scenario 2 is based on a somewhat more realistic, but still massive, conversion of cropland. Although arbitrary, both scenarios resemble land-cover and management-change scenarios suggested by currently proposed strategies (IPCC 2007; MNCCAG 2008). Mean C sequestration rates for some of the most ecologically feasible land-cover and management changes for the region were matched with current land-use inventories for agriculture, grassland, and forest, to calculate the potential area of land available for conversion and to develop C sequestration estimates.

Scenarios

Scenario 1

This seeks to quantify the land area necessary to sequester 29% (~106 Tg C yr^{-1}) of 2004 regional C emissions (equal to two one-seventh fractions or "wedges" of the total 2004 emissions, sensu Pacala and Socolow 2004) through a combination of land-cover and management changes (Table 1) and their associated sequestration rates (Figure 1). We focused on those land-cover and management changes that have the greatest C sequestration rates that are ecologically feasible over large areas. Attaining a 29% emission reduction for the region would require converting 50 million ha (two-thirds) of existing agricultural land in the area into forests, grasslands, or prairie pothole wetlands, as ecologically appropriate, as well as enhanced stocking of 30 million ha of existing forests. The cropland acres lost in the Upper Midwest in this scenario constitute nearly 40% of the harvested cropland acres and a disproportionate 49% of all grain, oilseed, and dry bean production in the US, a huge economic loss impacting other sectors of the agricultural and food-processing industry dependent on these yields. The combination of practices assigned to each state, and the absolute and relative contributions in terms of C sequestration and mitigation potential attributed to them, are provided in Table 1.

The resulting figures are optimistic with respect to the magnitude of C sequestered per unit of land converted, for the reasons stated above. Furthermore, they assume that enhanced forest stocking will produce fully stocked forest stands; in reality, forests are generally "understocked" for a variety of reasons (poor, wet, or rocky soils; competition from dominant trees; disease and herbivory) that limit the establishment and growth of trees. Thus, the actual gains in stocking and in C sequestered would probably be considerably less than projected in this scenario; consequently, the area of land conversion required to achieve a 29% emission offset would be even larger.

Scenario 2

This estimates the proportion of regional CO_2 emissions that could be offset if 10% of the total harvested cropland in each state in the region were converted into forests or grasslands, as ecologically appropriate; if additional land, equal to 10% of the original prairie pothole habitat, was restored; and if 25% of all currently understocked forests were successfully restocked. The absolute and relative contributions to C sequestration and mitigation potential estimated by state are provided in Figure 2. Converting the harvested cropland area (7.4 million ha) considered in this scenario would more than double the current (as of 2006) land area (6.35 million ha) set aside in this region through enrollment in the Conservation Reserve Program (US Department of Agriculture Farm Service Agency). Despite taking an enormous area of agricultural land out of production, this strategy would, at best, mitigate only 4.7% of current CO_2 emissions for the region (Figure 2).

Both of the scenarios described above provide conservative estimates of the potential for GHG mitigation by land-cover and management change. Any scenario that removes large areas of agricultural land from production will greatly reduce global food supplies (Field *et al.* 2007), which are already insufficient to meet worldwide needs, and would most likely be countered by a corresponding conversion of forest or other high C-stock ecosystems elsewhere in the world into agricultural production. Deforestation is still occurring in various parts of the

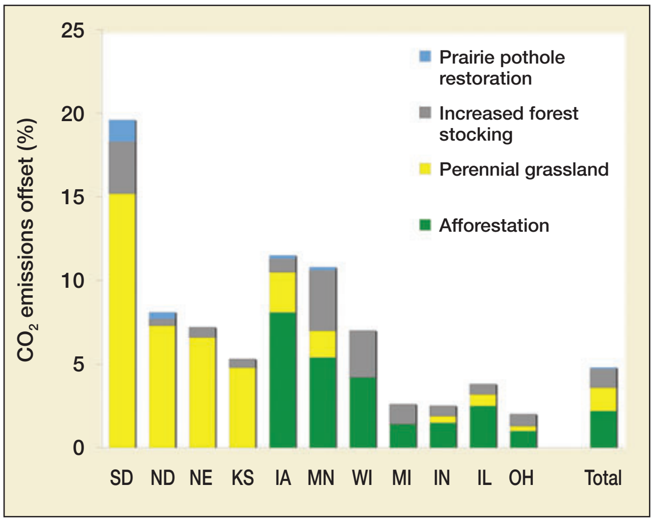

Figure 2. *State-by-state potential of percent fossil-fuel CO_2 emissions (2004) mitigation, as a result of converting 10% of harvested cropland, restocking 25% of understocked forests, and restoring 10% of prairie potholes in the Upper Midwest of the US. A similar percentage of harvested cropland (10%) was converted to forest and/or perennial grasslands in each state, depending on land availability and ecological suitability. Improved stocking refers to the restocking of 25% of currently understocked forests (50% of all forest land). In four states within the prairie pothole region (MN, IA, SD, and ND), C sequestration from restoration of prairie pothole wetlands was calculated for an additional area of harvested cropland equivalent to 10% of presettlement prairie pothole area. States are ordered according to individual CO_2 emissions, from low to high. Regional total estimates are also provided for comparison.*

world and further "leakage" would more than negate any net C emission reductions obtained by the initial conversion.

The scenarios described above use land-cover and management changes identified as providing the largest per hectare sequestration potential and that are ecologically feasible over extended areas in the region. Other land-cover and management changes that were not included in these analyses would provide only modest C sequestration, even if applied over large areas, because their C sequestration rates are considerably lower (Figure 1).

Conservation tillage has received considerable attention in the past decade as a potential C sequestration tool, because of the possibility of applying this practice on vast areas of land (Lal 2004; Grace *et al.* 2006), while still maintaining those lands in agricultural production. Early estimates indicated that conservation tillage could offset a substantial proportion of total C emissions; however, those estimates were based on much higher C sequestration rates for conservation tillage than are currently believed to be true and on the conversion of more than 75% of all cropland in the US to no-till by 2020 (Lal 1997). Similarly high estimates were based on models that predicted higher C sequestration in conservation tillage, based on assumed greater plant material return to soil than in conventional tillage (Grace *et al.* 2006). Applying the (highly uncertain) mean C sequestration rate for conservation tillage (Figure 1) that we obtained from empirical studies for the region to all harvested cropland in the Upper Midwest (circa 70 million ha [58% of US cropland]) would sequester 8.4 Tg of C, equivalent to only 2% of 2004 regional emissions, suggest-

Table 1. Carbon sequestration potential of different land-cover changes in the Upper Midwest of the US required to offset 29% of CO_2.

		C sequestration potential of land-cover and management change						
State	*Cropland area converted (*)*	*Row crop to forest*	*Row crop to perennial grassland*	*Prairie pothole restoration (†)*	*Optimal forest stocking (¶)*	*Total*	*Fossil-fuel emissions*	*Relative emission offset*
	Million ha	*Tg CO_2 yr^{-1}*					*Tg CO_2 yr^{-1}*	*%*
Minnesota	6.2	35.9	10.5	1.7	14.3	62.4	100	62
Wisconsin	2.2	29.6			11.8	41.5	107	39
Michigan	1.3	17.2			8.8	26.0	187	14
Illinois	5.7	38.6	11.4		5.3	55.3	236	23
Indiana	3.4	23.2	6.8		5.3	35.2	233	15
Ohio	2.6	17.5	5.2		7.6	30.3	262	12
Iowa	7.3	43.1	12.7	1.7	2.5	60.0	80	75
South Dakota	4.4		13.8	1.7	1.7	17.3	14	126
North Dakota	6.6		22.7	1.7	0.8	25.2	47	54
Nebraska	4.7		19.0		1.0	20.0	43	47
Kansas	6.1		24.4		1.9	26.4	77	34
Regional total	50.5	205.1	126.5	7.0	61.0	399.6	1386	29

Notes: Equal area was converted into forests and grasslands, where both land uses were ecologically likely, or entirely to either land use when the one or the other was ecologically unlikely, assuming a constant fraction (65%) of total converted agricultural land in each state (see WebPanel 1). (*) Does not include forest area to optimize stocking. (†) Equally partitioned among states that have this habitat type. (¶) Assumes increasing stocking in 100% of understocked forests.

ing that previous projections of C mitigation resulting from conservation tillage have been overly optimistic.

Conclusions

The results of this study show that terrestrial C sequestration has, at best, only limited potential to offset GHG emissions for the Upper Midwest of the US, a region with moderate emissions and large areas of cropland. This potential for mitigation is tightly constrained by the relatively low areal C sequestration rates associated with most land-cover and management changes and the limited availability of C-depleted, non-agricultural lands for conversion to land-use and land-cover types that have higher C sequestration rates. Any GHG mitigation scenario that takes large tracts of land out of agricultural production will very probably generate leakage elsewhere, thereby negating any potential benefits, unless major worldwide market regulations and policies are introduced in the near future to prevent leakage from happening.

Although some state policy reports have noted the modest C mitigation potential achievable through land-cover and management changes (Center for Clean Air Policy 2005), others have viewed this potential as considerable (MNCCAG 2008). Regional estimates, like the one proposed here, represent a critical step toward the development of global-scale assessments of terrestrial C sequestration potential. This study highlights the need to develop accurate and realistic regional estimates of C sequestration potentials, as well as their capacity to mitigate current C emissions and their possible impacts on the world food supply, regional economies, and land-use activities elsewhere. Otherwise, overestimation of potential benefits from terrestrial C sequestration, such as those highlighted in this study, could potentially divert the attention of policy makers from other, more feasible, realistic, and cost-effective GHG mitigation strategies.

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WebPanel 1. Additional information on methods

We selected land uses that are common to the Upper Midwest of the US (11 states: IA, IL, IN, KS, MI, MN, ND, NE, OH, SD, and WI) and evaluated their potential to sequester atmospheric C upon conversion from current land use. Land-use changes included converting existing annual row crops to forests, short-rotation woody crops, prairie potholes, perennial grasslands, and pasture or hay land; converting turfgrass to urban woodland; restoring peatlands; introducing conservation tillage; incorporating cover crops into annual row crops; increasing diversity of grasslands; and improving forest stocking in understocked stands.

Carbon sequestration rates were calculated as the yearly accrual of C resulting from conversion to each new land use, based on the available literature and data relevant for the region. Compiled data came from empirical studies conducted in the Upper Midwest and other nearby locations, and from analyses of existing databases (eg the USDA Forest Service Forest Inventory Analysis database [FIA]). Modeling studies were excluded from the analyses. The estimates of C sequestration rates (in Mg C ha^{-1} yr^{-1}) are average for each land-use change category. When values of C sequestration rates were available for multiple sites or forest stands within the same source, we treated each value as a unique observation (n = 2, 3,…, i). Conversely, when the C sequestration rate was presented by authors as a mean value for multiple sites or stands, we treated the mean as a single observation (n = 1). Exceptions include improved forest stocking and prairie pothole restoration, where it was possible to estimate C sequestration rates by linear regression of C stocks against age since conversion across different sites. With the exception of short-rotation woody crops, we assumed that C sequestration rates will be approximately linear for at least 50 years following conversion for all land-use/land-cover changes; consequently, our estimates only apply to the first 50 years after conversion.

Terrestrial C sequestration potential for the Upper Midwest was obtained by multiplying C sequestration rates of selected land-use changes (ie those with the greatest potential to sequester C per unit area: reforestation/afforestation, perennial grasslands, prairie pothole restoration, and improved forest stocking) by the area to be converted, as described in (1).

For Scenario 1, estimates assume that terrestrial C sequestration can account for about 29% of global emissions, equivalent to two one-seventh fractions (or "wedges") of the total 2004 CO_2 emissions (2). CO_2 emissions from fossil fuels for each state (Tg CO_2 ha^{-1} yr^{-1}) are based on data from EPA (2004) (3).

To estimate the land-use changes required to offset 29% of these emissions in the entire 11-state region, we first calculated the CO_2 offsets resulting from the stocking of 100% of understocked forest stands in each state by multiplying the CO_2 sequestration rate for stocking by the area of understocked forests in each state. Then, we calculated the CO_2 offsets resulting from the restoration of 100% of prairie pothole habitat in the region. This corresponded to the CO_2 sequestration rate of prairie pothole restoration multiplied by the area of original prairie pothole habitat in the region (~3.84 Mha)(4). We assumed this area to be evenly distributed in the croplands of four states in the region: IA, MN, SD, and ND; finally, we calculated the agricultural land area conversion required to offset the residual emissions in the entire region. For this purpose, we considered two types of land-use changes, conversion of cropland to forests and/or to perennial grasslands, and calculated the land area needed, based on the sequestration rates of each land-use change, assuming that the same proportion of agricultural land was converted in each state.

For Scenario 2, we calculated the C mitigation that can be derived from the conversion of 10% of all agricultural land in each state by multiplying this area by the CO_2 sequestration rate of each of three selected land-use changes as above. In addition, we estimated the C sequestration associated with improving the stocking of 25% of understocked forest land in every state with forests. We used the same proportion of agricultural land to be converted to forests and/or grasslands in each state, as in Scenario 1, and calculated the mitigation potential by state and for the entire 11-state region (ie percentage of total CO_2 sequestration relative to total CO_2 emissions). For those states in the prairie pothole region, we dedicated an additional area of cropland for prairie pothole restoration that corresponded to 10% of the original (pre-European settlement) prairie pothole area (3.84 Mha) (5). The restored area of prairie pothole wetlands was added to the 10% of total cropland dedicated to reforestation and/or grassland conversion, but this represented only a small additional land area (0.4 Mha of 7.0 Mha converted to forests and/or grasslands), resulting in a final cropland conversion of 10.5% for the entire region.

In both Scenarios 1 and 2, conversion of agricultural land to forests and improved forest stocking were restricted to those states where a substantial area of agricultural land was created by forest clearing during European settlement (OH, IN, IL, MI, WI, MN, and IA). Conversion of cropland to perennial grasslands was assumed for those states where a large area of cropland was created from natural prairies during European settlement (OH, IN, IL, MN, IA, KS, NE, SD, and ND). In states where agricultural land can be converted to both forests and grasslands (IA, IN, IL, MN, and OH), we assumed a conversion of 5% of the state's cropland to each land use (for a total of 10%). This area was equally distributed among these five states.

Calculation of C sequestration rates for different conversions of land-use and management practices.

Carbon sequestration rates were calculated from data in the literature (WebTable 1). The following text details the procedures used in the calculation of the rates for each land-use and management practice conversion.

(1) Peatland restoration

Because of the dearth of measured data concerning changes in C sequestration upon restoration of wetlands, the data we pre-

WebPanel 1. Additional information on methods – *continued*

sent are the average of C sequestration rates in undisturbed peatlands from North America. Data used for our estimates were obtained either from micrometeorological (eddy covariance) measurements of whole-ecosystem CO_2 flux over peatlands or from dating deep peat cores and assuming a linear rate of peat accrual over the existence of the peatland. Because of the sampling methodologies associated with these types of studies, this estimate includes accumulation of C in both vegetation biomass and soil.

(2) Prairie pothole restoration

Estimate is based on a chronosequence-based study (4) that used multiple sites spread across the prairie pothole region (MN, IA, ND, SD). The chronosequence included restored prairie pothole wetlands that had been converted from agricultural land uses at different times in the recent past, allowing quantification of C sequestration rates in plant biomass and soils. We only present the rates of C accumulation in soils, as we assume that C sequestration in plant biomass will saturate relatively quickly (within a few years) in these and other systems dominated by herbaceous vegetation. All studies were conducted in recently restored wetlands (2 to 12 years old) and the mean C sequestration rate was obtained from regression analysis over 27 sampling sites.

(3) Annual row crops to forest

The studies used to determine the estimates provided in this study were paired comparisons between afforested agricultural land and nearby agricultural fields and include coniferous and deciduous forests from nearby states (IN, MI, OH, WI) and the Canadian province of Ontario for a total *n* of 11 (total biomass) and seven (soil) studies. At these sites, conversion to forest occurred between 10 and 90 (mean = 54) years before sampling. For the studies that measured changes in belowground biomass, the mass of coarse roots averaged 16% of that of aboveground biomass. Therefore, for those studies where only aboveground biomass was reported, we assumed the contribution of coarse roots to be an additional 16% of aboveground biomass.

(4) Annual row crops to short-rotation, woody crops

Fast-growing trees are used in short-rotation cycles (typically < 20 years) for biomass production, and hybrid poplar and willow are the most common species used in the northern US. Estimates of C sequestration rates are based on measured changes in C sequestration following establishment of a stand or following the conversion from annual row-crop agriculture to short-rotation, woody crops. The potential of short-rotation woody crops to offset anthropogenic CO_2 emissions largely depends on the fate of the woody biomass after harvesting and the life cycle of the products. Utilization of biomass for biofuels may indirectly provide additional offsets to CO_2 emissions by reducing use of fossil fuels. If harvested biomass is used for paper production, the rate of C sequestered during the short-rotation cycle after harvest depends on the ultimate fate of the products. However, paper products generally have a rapid turnover time. The long-term C sequestration potential of this type of short-rotation management could therefore be comparatively low if full C accounting is considered.

(5) Management of existing forests – increased forest stocking

We used data on biomass accumulation of forests under different stocking conditions from the 2005 USDA-FS Forest Inventory Analysis (FIA) database for states with high forest cover in the Upper Midwest (MI, WI, and MN) to estimate C sequestration rates following improved stocking of understocked stands. In the first 30 years of stand development, biomass accumulates linearly, so we determined rates of C sequestration from the slope of the relationship between C in biomass and stand age for each stocking category separately. This value does not include C sequestration in the soil, because increased stocking is expected to have lower effects on the soil than on the standing biomass of the forest. To estimate the stocking effect on C sequestration rates, we used the difference in C sequestration rates from insufficient to fully stocked stands, including poor and medium stocking in the insufficient stocking category.

We also used the FIA database (2006) to estimate the forest area by state and in the entire region that was understocked. The percentage of current forests attributed to the "understocked" and "medium stocked" categories ranged from 48% to 55% in highly forested states (MI, WI, and MN) and was around 50% in the entire region. In states with little forest cover, this number reached 80%. However, we decided to use a unique percentage (50%) for all states in the region, to avoid including sites with very low productivity (predominant in non-forested states) in the area of stands amenable for stocking.

(6) Annual row crops to pasture and hay land

Carbon sequestration in pastures and hay lands differs from that in perennial grasslands because of the effects of grazing, fertilization, and harvesting of the aboveground biomass, and their effects on C and nutrient cycles. Rates of C sequestration can vary greatly, depending on vegetation type and management (particularly manure management), making any estimate extremely difficult to extrapolate. Because of the lack of an extensive dataset, our estimate is based on three paired comparison studies between pastures or hay lands and adjacent row crops. The studies had different species compositions and spanned observation periods from 3 to 20 years.

(7) Annual row crops to perennial grassland

The estimate of C sequestration upon conversion of agricultural row crops to perennial grassland derives from the analysis of 24 studies that were either paired agricultural land and former agricultural land converted to perennial grassland or chronosequence studies of lands converted to perennial grassland. The states considered here (IA, KS, MI, ND, NE, OH, WI)

WebPanel 1. Additional information on methods – *continued*

encompass the region that was once tallgrass or mixed-grass prairie. The greatest C sequestration in these studies occurs in the top 10 cm of soil, while C sequestration is nearly undetectable at a depth of 100 cm or greater during the time frame of these studies. Soil starts sequestering C soon after the conversion into perennial grassland (circa 5 years) and appears to still be accumulating C 40–60 years after conversion, as shown by comparison with nearby grassland soils that had never been cultivated (eg Conant and Paustian 2001).

(8) Conventional to conservation tillage

The estimated C sequestration potential provided here derives from the analysis of 16 studies conducted in the upper Midwestern states. The majority of these data were obtained from side-by-side comparisons between sites with conventional tillage and those with reduced tillage. Sampling depths for these studies varied between 20 and 100 cm. One set of results was obtained from paired fields measured with eddy covariance micrometeorological methods. Recent studies conducted in MN and NE via micrometeorological methods showed no difference between conventional and no-tillage (Baker *et al.* 2007).

(9) Inclusion of cover crops in row-crop systems

The estimated C sequestration rates that occur with the use of cover crops come from comparisons between row cropping systems that did not use cover crops versus those that included different species (rye, winter wheat, oats, and others) as cover crops. This estimate was obtained from the analysis of only four studies in the Midwest and includes the use of different species as cover crops.

(10) Low-diversity to high-diversity grasslands

Differences in soil C cycling in grasslands may derive from variation in the level of plant species diversity and composition because of greater resource use and productivity by species-rich mixtures compared to species-poor communities. Here, we focused on comparisons of low-diversity communities dominated by cool-season grasses with high-diversity communities dominated by a mixture of prairie species, as this comparison is most relevant to understanding how grasslands in set-aside programs or roadside right-of-ways that are dominated by cool-season grasses (eg smooth brome) might change if managed for higher species diversity in the future. For our estimates, we referred to four studies that compared soil C accumulation rates under grassland communities that varied in species diversity. Two studies compared C sequestration rates in monocultures of a single grass species with rates in diverse prairies. Two additional studies compared rates in species-rich mixtures with rates in monocultures of both grasses and forbs. For these latter two studies, we compared the mean of species-rich mixtures with the mean of grass species monocultures (ie we excluded forb monocultures from our analysis). However, the standard deviation between studies was one order of magnitude greater than the mean, with some studies showing lower C sequestration in diverse mixtures than in monocultures, indicating a great deal of variability in this estimate among the very low number of studies.

(11) Turfgrass to urban woodland

The estimates of C sequestration rates in urban forests derive from a single study of the US Department of Agriculture in the city of Minneapolis, MN. The estimate considers only above-ground biomass, due to lack of information on and extreme variability of soil C sequestration in urban areas that are climatically similar to MN. Carbon sequestration rates in urban forests can vary greatly, depending on tree age and size. Because this estimate comes from a single study, we do not present any estimate of the uncertainty associated with it.

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WebTable 1. Summary of empirical data from available literature used to obtain values for C sequestration rates in plant biomass and soil for alternative land-use/land-cover changes.

Land-use/land-cover change by sector	*Location*	*Time since conversion (yr)*	*Max soil sampling depth (cm)*	*Dominant plant cover*	*C sequestration rate*		*Source*
					Total biomass	*Soil*	
					(g C m^{-2} yr^{-1})		
Wetland							
Peatland restoration	**Mean (SD)**				**45 (20)[a]**		
	Ottawa			Moss and shrubs	60[a]		Moore *et al.* (2002)
	US			Bog, mosses	25[a]		Gorham *et al.* (1991, 2003)
	Ottawa			Moss and shrubs	68[a]		Lafleur *et al.* (2001, 2003)
	US			Various peatland spp	48[a]		Armentano and Menges (1988)
	Ottawa			Shrubs, sedges, moss	22[a]		Roulet *et al.* (2007)
Prairie pothole restoration	**Mean (SD)**					**305 (NA)**	
	ND, SD, MN, IA	2–12	15	Mixed native wetland spp		305	Euliss *et al.* (2005, 2006); Gleason *et al.* (2005)
Forestry							
Annual row crops to forests	**Mean (SD)**				**330 (116)**	**37 (24)**	
	MI	53	100	Deciduous trees	200	35	Morris *et al.* (2007)
	MI	50	100	Conifer trees	200	26	Morris *et al.* (2007)
	Ontario	20	41	Deciduous trees	420		Paul *et al.* (2003)
	Ontario	23	41	Conifer trees	320	56	Paul *et al.* (2003)
	OH	50	100	Deciduous trees	380	58	Paul *et al.* (2003)
	OH	50		Conifer trees	240		Paul *et al.* (2003)
	OH	50	100	Deciduous trees	200	15	Paul *et al.* (2003)
	MI	10		Deciduous trees	485[b]	79	Degryze *et al.* (2004)
	IN	80		Deciduous trees	533		Curtis *et al.* (2002)
	MI	90		Deciduous trees	344		Curtis *et al.* (2002)
	WI	66		Deciduous trees	321		Curtis *et al.* (2002)
	OH	80	80	Deciduous trees		51	Puget and Lal (2005)
Annual row crops to short-rotation woody crops	**Mean (SD)**				**372 (154)**	**97 (93)**	
	Central US	12–18	100	Poplar	340	163[c]	Hansen (1993)
	Quebec	4	60	Willow	170		Zan *et al.* (2001)
	MI	10		Poplar		32	Degryze *et al.* (2004)
	Quebec	16–18		Willow and Poplar	600		Labrecque *et al.* (2005)
	MN	10		Poplar	350		Hussain *et al.*
	Germany	5–10		Poplar	400		Liesebach *et al.* (1999)
Agriculture							
Annual row crops to pasture	**Mean (SD)**					**29 (9)**	
	ND	3		Mixed prairie spp		25	Frank (2002)
	ND	3		Wheatgrass		20	Frank (2002)
	GA	20	20	Fescue/bermudagrass		38	Franzluabbers (2000)
Annual row crops to perennial grassland	**Mean (SD)**					**107 (108)**	
	IA	10	30	Tallgrass prairie		390	Al-Kaisi *et al.* (2005)
	NE	10	5	Tallgrass prairie		58	Baer *et al.* (2002)
	MI	10	50	Mixed native		79	Degryze *et al.* (2004)
	IA,MN	7–9	20	Mixed grasses		–27	Follet *et al.* (2001)
	NE	6	20	Mixed grasses		94	Follet *et al.* (2001)
	ND	10	20	Mixed grasses		59	Follet *et al.* (2001)
	KS	5	300	Native blue grama, wheatgrass, etc		296	Gebhart *et al.* (1994)
	KS	5	300	Native blue grama, wheatgrass, etc	66		Gebhart *et al.* (1994)
	NE	5	300	Native blue grama, wheatgrass, etc	106		Gebhart *et al.* (1994)
	IL	10	10	Tallgrass prairie		70	Jastrow (1987)
	MN	6.5	7.5	Mixed		22	Karlen *et al.* (1999)

Continued

WebTable 1. Summary of empirical data from available literature used to obtain values for C sequestration rates in plant biomass and soil for alternative land-use/land-cover changes – *continued*

Land-use/land-cover change by sector	*Location*	*Time since conversion (yr)*	*Max soil sampling depth (cm)*	*Dominant plant cover*	*C sequestration rate: Total biomass ($g\ C\ m^{-2}\ yr^{-1}$)*	*C sequestration rate: Soil ($g\ C\ m^{-2}\ yr^{-1}$)*	*Source*
	IA	2.5	7.5	Mixed		180	Karlen *et al.* (1999)
	IA	6	7.5	Mixed		12	Karlen *et al.* (1999)
	ND	5.3	7.5	Mixed		42	Karlen *et al.* (1999)
	MN	61	10	Mixed grasses and legumes		20	Knops and Tilman (2000)
	WI	12	5	Native prairie		25	Kucharik *et al.* (2003)
	WI	4–16	20	Native prairie		76	Kucharik *et al.* (2007)
	OH	15	30	Mixed pairie		330	Lantz *et al.* (2001)
	OH	45	30	Mixed pairie		20	Lantz *et al.* (2001)
	OH	45	30	Mixed pairie		220	Lantz *et al.* (2001)
	NE	130	33			62	Martens *et al.* (2003)
	MN	40	20	Mixed grasses and legumes		109	McLauchlan *et al.* (2006)
	Central US			Mixed grass		40	Sperow *et al.* (2003)
	IN	8	100	Tall mixed grasses		210	Omonode and Vyn (2006)
Conventional to conservation tillage	**Mean (SD)**					**12 (40)**	
	IA	7	30	Corn–soybean		80	Al-Kaisi *et al.* (2005)
	MN	13	30	Corn		–3	Allmaras *et al.* (2004)
	Canada	6	60	Corn		10	Angers *et al.* (1997)
	MN	2		Corn–soybean		0	Baker and Griffis (2005)
	MN	13	30	Corn		–8	Clapp *et al.* (2000)
	Ontario	25	60	Corn–soybean		42	Deen and Kataki (2003)
	MN	23	45	Corn–soybean		0	Dolan *et al.* (2006)
	IN	28	100	Corn–soybean		35	Gal *et al.* (2007)
	ND	12	30	Wheat		57	Halvorson *et al.* (2002)
	IA	15	20	Corn		61	Karlen *et al.* (1998)
	IL	12	75	Corn–soybean		25	Olson *et al.* (2005)
	OH	1	30	Corn		–30	Owens and Shipitalo (2004)
	OH	8	80	Corn–soybean		50	Puget and Lal (2005)
	MN	15	60	Corn–soybean		–8	Venterea *et al.* (2006)
	Ontario	6	50	Corn		–21	Wanniarachchi *et al.* (1999)
	Ontario	29	50	Corn		–2	Wanniarachchi *et al.* (1999)
	IL	8	90	Corn–soybean		–5	Yang *et al.* (1999)
Inclusion of cover crops in row crops	**Mean (SD)**					**40 (22)**	
	MN			Rye		71	Baker (2005)
	MN			Rye		30	Griffis, unpubl.
	ND	30.5		Winter wheat		37	Halvorson *et al.* (2002)
	US			Various spp		20	Lal *et al.* (1998)
Perennial grassland							
Low diversity to high diversity grassland	**Mean (SD)**					**5 (95)**	
	ND	3		Prairie vs wheatgrass		20	Frank (2002)
	IN	6–8	100	Tall grass mixed spp vs switchgrass		–131	Omonode and Vyn (2006)
	MN	7	100	Diverse grass–forb mixture vs grass monoculture		84	Reich *et al.* unpubl (Biocon)
	MN	12	60	Diverse grass–forb mixture vs grass monoculture		49	Tilman *et al.* (2006) and unpublished
Urban							
Turfgrass to urban woodland	**Mean (SD)**				**240 (NA)**		
	MN			Various tree spp	240		USDA Report (2006)

Note: Where studies presented estimates from more than one location (site, forest stand, etc.), we included each as an individual observation. a = values are cumulative C sequestration rates; b = root contribution calculated as 16% of aboveground biomass; c = includes root biomass; NA = not available because only one study was available; SD = standard deviation.

