The Potential for Terrestrial Carbon Sequestration in Minnesota

A Report to the Department of Natural Resources from the Minnesota Terrestrial Carbon Sequestration Initiative

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1. Introduction

Terrestrial ecosystems have the potential to take up carbon (C) from the atmosphere and store it, thereby mitigating, at least temporarily, some of the increase in atmospheric carbon dioxide (CO_2) that is occurring largely as a result of fossil fuel emissions. However, the capacity for terrestrial ecosystems to sequester CO_2 emitted from fossil fuel combustion is poorly understood and thus terrestrial C sequestration is difficult to include in policies aimed at reducing net CO_2 emissions. In light of the ambitious CO_2 emissions reductions targets established under Minnesota's Next Generation Energy Act, the Minnesota State Legislature (HF No. 1666, Minnesota Law 2007, ch. 57, article 2, section 3) has requested that the University of Minnesota produce an assessment of the potential capacity for C sequestration in Minnesota's terrestrial ecosystems. This report provides the requested assessment, summarizing data from the literature to 1) discuss those C stocks that are most vulnerable to emitting significant C to the atmosphere if disturbed by human activities or other disturbance, 2) describe the potential for changes in C sequestration following various land use/land cover changes, 3) discuss policies and programs in the state of Minnesota that are relevant to C sequestration related to land use/land cover, and 4) develop scenarios showing the amount of C that might be sequestered in Minnesota landscapes by various land use/land cover changes.

This report uses a comprehensive and critical review of the scientific literature to assess the capacity for direct sequestration of C by terrestrial systems, focusing on ecosystems common to Minnesota and the central part of North America. Carbon sequestration is defined (by the legislation) as "the long-term storage of C in soil and vegetation to prevent its accumulation in the atmosphere". Terrestrial C sequestration occurs when the rate of plant uptake of CO_2 from the atmosphere exceeds the rate of CO_2 return to the atmosphere from plant respiration plus decomposition by soil microorganisms (Fig. 1.1). Plants take up CO_2 during photosynthesis and incorporate some of it into their own biomass. When whole plants or plant parts die, C is transferred to soils where it is ultimately converted back into atmospheric CO_2 (or methane, CH_4) through decomposition by soil organisms. Sequestration occurs when time lags exist between the processes of C uptake and C return to the atmosphere, either because C is incorporated into plant tissues like wood that live for a long time, or because it is incorporated into the soil where characteristics of the environment (or the plant tissues themselves) slow the rate of decomposition. For example, chemically complex plant parts decompose very slowly. Also, cold temperatures and low oxygen conditions such as those found in waterlogged soils (e.g., peatlands) greatly slow the activity of soil organisms, and thus the rate of decomposition, promoting C sequestration. When plants or plant parts are harvested, the harvested C also eventually returns to the atmosphere. This return is relatively rapid if harvested C is consumed and digested (by humans or animals), burned (in the case of biofuels), or used to manufacture paper or other products that decompose relatively quickly. The C return to the atmosphere is delayed if harvested C is used for lumber or other products that last a long time before eventually decomposing.

This report focuses on quantifying the effects of changes in land use or land cover on C sequestration because such changes in land use/land cover often trigger a change in C sequestration rates and thus can be targeted by specific policies to enhance terrestrial C sequestration. Changes in land use that speed up decomposition rates (and CO_2 return to the atmosphere) exacerbate the increase in atmospheric CO_2 occurring from fossil fuel emissions. For example, when peatlands or other wetlands are drained, the drainage greatly improves the aeration of the soil, providing decomposers with more oxygen and speeding up their activity. This accelerates the transfer of large amounts of C from soils to the atmosphere, adding to the atmospheric CO_2 burden. On the other hand, some land use or land cover changes may increase the rate of C sequestration either because CO_2 uptake by plants is enhanced, and/or because the rate of decomposition and CO_2 return to the atmosphere is slowed. For example, conversion of row crop agriculture to perennial grassland or forest slows the return of C to the atmosphere because the aboveground vegetation is not harvested and thus relatively more C is transferred to soil. Restoration of peatlands and other wetlands increases terrestrial C sequestration because harvest ceases and because the rate of decomposition of soil C is drastically reduced under the restored waterlogged conditions. Land use or land cover changes can increase C sequestration rates only for a finite period of time (decades to a couple of centuries), depending on the specific land conversion, until the ecosystem reaches what is termed a new "steady-state", when C uptake and C return to the atmosphere are in balance. This steady state arises because plants cannot keep growing bigger and bigger indefinitely—plants eventually reach a state when their growth simply replaces parts that die and C sequestration in plant biomass stops. Eventually, C sequestration in soils also stops: as C accumulates in the soil from plant inputs, the rate of C return to the atmosphere increases proportionately, eventually matching C inputs (peatlands are somewhat of an exception and may, under some circumstances, sequester C for a much longer time).

Besides the direct C sequestration that can occur in plants and soil upon land use/land cover conversion, there are other sources of CO_2 exchange with the atmosphere associated with land use/management practices that must be considered in a full accounting of C sequestration. These include both on- and off-site emissions associated with the establishment and maintenance (tillage, fertilizer and pesticide production and application) of the proposed land use/management practices, and the harvest and transportation (if any) of crops or forest biomass. The post-harvest fate of C in secondary products (e.g., wood, paper, biofuels, grain) is also part of a full accounting of net C sequestration. As mentioned previously, products that have a long life (e.g., lumber) would sequester C from the atmosphere for a longer time than products with a shorter life (e.g., paper). And, in the special case of biofuels, the energy use associated with their production and transportation and the net quantity of fossil fuel C they may replace must also be considered. Analysis of C exchange processes other than direct sequestration is clearly important, but is beyond the scope of this report. Those processes should, however, be carefully and thoroughly assessed prior to promotion and/or implementation of any land use/management systems for C sequestration.

In the sections that follow, we detail our specific findings regarding the capacity of changes in terrestrial land use and land cover to sequester C and offset fossil fuel emissions. Our most important findings are that (1) peatlands and forests in Minnesota contain very large C stocks, and should be protected to preserve intact those C stocks and prevent additional large emissions of CO_2 to the atmosphere, and (2) certain land use practices and land cover changes have significant potential to increase C sequestration. The practices with the most potential include conversion of annual row crops to forests and short-rotation woody crops, and restoration of prairie potholes. Conversion from annual row crops to perennial grassland, conversion of turfgrass to urban woodland, increased stocking of understocked forests, and peatland restoration would also provide positive C sequestration. Although the total capacity for terrestrial C sequestration is relatively modest (likely amounting to at most a few percent of Minnesota's current total CO_2 emissions), all of these land use/land cover changes are associated with additional environmental benefits (e.g., increased water quality or biodiversity) and hence should be promoted, either by new policies or by revision/enhancement of existing policies.

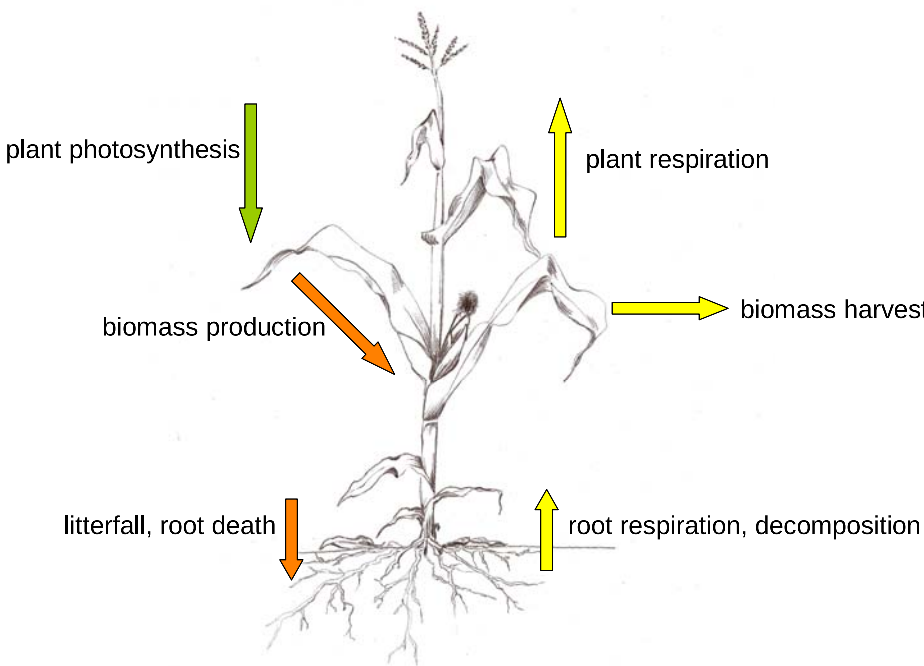


Figure 1.1. A simplified diagram of C cycling in a terrestrial plant-soil system. Green arrows indicate CO_2 uptake by plants through photosynthesis. Orange arrows indicate incorporation of C into biomass and C inputs to soil from the death of plant parts (litterfall and root death). Yellow arrows indicate C return to the atmosphere through plant respiration or through the decomposition of litter and soil C by soil organisms. Carbon in harvested tissues also eventually returns to the atmosphere during digestion (by humans and animals), combustion, or eventual decomposition.

2. Major land use/land cover categories

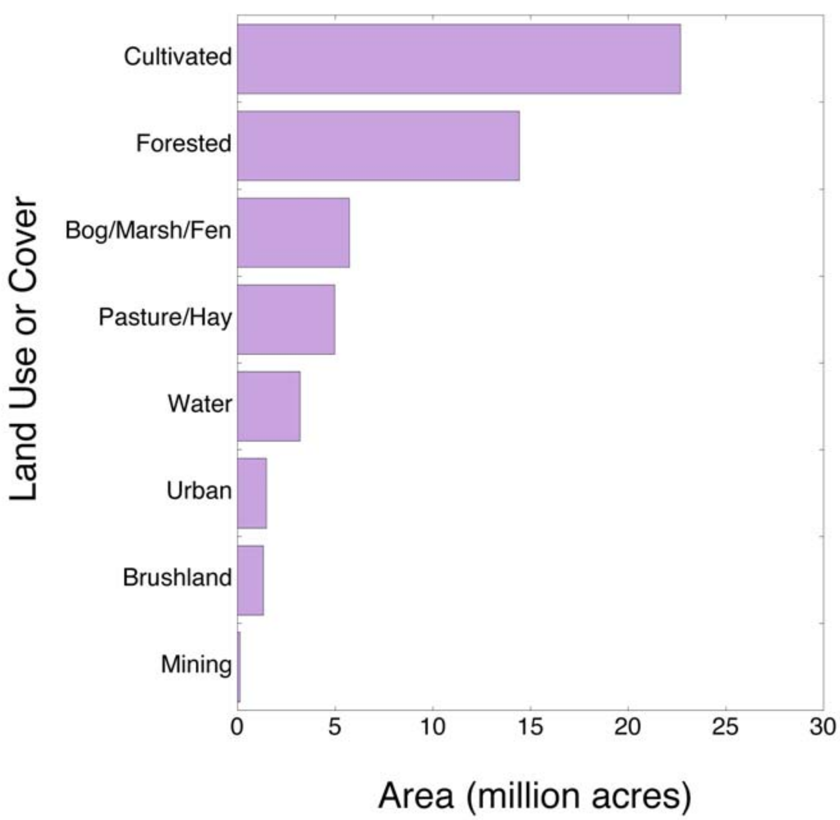
Various land uses and land covers currently store different amounts of C. The data in Table 2.1 and Fig. 2.1 below show the total acreage for the major land use/land cover categories as provided by Land Management Information Center (LMIC) for 1990 (although much of these data have been separately updated, this is the last comprehensive land cover category data for Minnesota). It should be clearly noted in Table 2.1 that the classification of a specific parcel or acre of land into a category is somewhat arbitrary. For example, a peatland that supports a black spruce stand could be classified in either the "Forested" or the "Bog/Marsh/Fen" categories. Discrepancies between acreages for various land use/land covers in these data and other, similar datasets, may be due to differences in class definitions.

Table 2.1 Areal extent of major land use/land cover categories in Minnesota.

Land Use Category	Million Acres in 1990[a] (percent of total)
Urban	1.47 (2.7)
Cultivated	22.69 (42.0)
Pasture/Hay	4.98 (9.2)
Brushland	1.33 (2.5)
Forested	14.43 (26.7)
Bog/Marsh/Fen	5.73 (10.6)
Mining	0.15 (0.3)
Water	3.21 (6.0)
Total	53.99 (100.0)

[a]Estimation based on LMIC data for 1990

Figure 2.1. **Areal extent of major land use and land cover categories in the state of Minnesota (1990 data).**



3. Potential for losses of carbon from peatland soils and forest biomass

Existing organic soils (bogs, fens, and marshes; hereafter referred to together as “peatlands”) and forests contain large stocks of C. Loss or significant degradation of these land cover types could transfer huge quantities of C to the atmosphere. Globally, peatlands represent just 3% of all soils but contain more than one-third of all soil organic C (Bridgham et al., 2001). A preliminary inventory of peatlands in Minnesota estimates that the 5.73 million acres of peatland in the state contain 4,250 Megatonnes (million metric tons) of C, or approximately 745 metric tons of stored C per acre. (Estimates based on data from the Minnesota DNR peatland inventory, the USDA-NRCS STATSGO and NASIS database, and the 1990 LMIC land cover data [Table 2.1, above]; see Appendix I for details).

Peatland soils are typically saturated with water during most of the growing season. Microbial activity is greatly decreased in the anaerobic conditions that develop in saturated conditions; thus biomass inputs from plants to soils in peatlands are only very slowly decomposed. Although the rates of plant growth and, thus C input to soils, are often low in peatlands, the rates of decomposition are even slower, with the net result that they accrete and store large, thick deposits of organic materials over long periods of time, including large stocks of labile (readily-decomposable) organic materials.

Drainage of peatlands by natural or human activities leads to aeration (i.e., increased oxygen) of the peats and much higher rates of decomposition of these labile organic materials, with the result that they often become significant sources of CO_2 to the atmosphere, rather than sinks. Although normally considered to be sinks for atmospheric C, C sequestration in peatlands can be reversed by artificial drainage for agriculture or to improve forest growth; construction of roads that can interfere with surface drainage patterns; and removal or destruction of peatlands for urbanization or other purposes. Likewise, changes in regional climate may also lead to lower water tables and increased aeration of peatlands, with subsequent loss of C. Decreases in precipitation can directly lower water tables and increases in temperature can cause increases in evaporation and transpiration, thus indirectly lowering water tables.

Preservation of existing peatlands and other high C wetland soils is already a priority in federal wetland preservation programs. Continued protection of peatlands, the single largest C stock in Minnesota, is important to prevent emission of additional quantities of greenhouse gases to the atmosphere. Loss of the C contained in a thousand acres of peatland would release approximately 2.7 million metric tons of CO_2 to the atmosphere, *increasing* Minnesota's total annual emission of CO_2 by 2 percent above 2005 levels.

Minnesota forests also have enormous C stocks in standing biomass. Estimates derived from forest inventories in Minnesota [US Forest Service Forest Inventory and Analysis Program (FIA)] and the Carbon Calculation Tool (Smith et al. 2007) indicate that by the year 2006 a total of 16.21 million acres of forests in the state contained 1,607 Megatonnes of C, or approximately 99 metric tons of stored C per acre. This is a decrease from 16.85 million acres and 1,713 Megatonnes estimated for 1990. The decrease in 635,000 acres of forest is in part responsible for the reduction of the forest C stock in 106 Megatonnes of during this period. Like peatlands, forest C stocks can be affected by climate change and human activities. Predicted changes in regional climate indicate higher seasonal temperatures and a lengthening of the growing season (Penuelas and Filella 2001). In North America, a longer growing season leads to delayed vegetation senescence (Piao et al. 2007). This, together with increasing atmospheric CO_2 levels, will likely increase C fixation rates and, potentially, increase C sequestration into forest biomass (IPCC 2007). Increases in temperature, however, can also lead to greater rates of plant (Amthor and Baldocchi 2001) and soil respiration and litter and soil organic matter decomposition (Davidson and Janssens 2006), all net sources of CO_2 that can negate the positive effects of temperature on net ecosystem C storage in forests (White and Nemani 2003). Furthermore, climate change may also alter rainfall patterns and cause extreme weather events such as summer droughts or floods that could reduce forest productivity and C sequestration potential.

Human activity leading to forest displacement by mining, urban sprawl, road construction, etc. can potentially produce substantial C loss, both from forest biomass and soil carbon. Indirect effects of human disturbance and climate change can also have negative effects on forest productivity. Mild winters and longer summers can lead to extended reproductive cycles of forest insect herbivores and pathogens or facilitate the spread of invasive pest species (Bale et al. 2002), leading to additional biomass losses. Substantial forest biomass losses can occur from summer fires resulting from drought and human activity. Although forests in Minnesota are currently exposed to less air pollution than many other areas in the U.S. (Miles 2007), future increases in urbanization may increase air pollution, particularly tropospheric ozone levels and acid rain, further damaging forest health and reducing C sequestration potential (Bytnerowicz et al. 2007).

4. Measuring carbon sequestration

Carbon stocks (the total amount of C present in any ecosystem component) are measured directly (as in soils or crops) by sampling and analysis of the material for C content or indirectly (as in forest biomass) by measurement of tree stand parameters (stand density, tree height and diameter) and followed by estimation of the C content of the aboveground biomass from established relationships.

Carbon sequestration rates (presented in this report in units of metric tons C or CO_2 per acre per year) are measured by several methods that can be summarized as:

- **Biomass Measurements**. Aboveground biomass is either measured directly by cutting and weighing (grassland/forb/shrub systems) or indirectly (for forests as described above for C stocks). Measurement of belowground biomass is much more difficult due to the mass of soil that needs to be excavated and the difficulty in separating fine roots from soil particles. Rates of sequestration in biomass are determined by longitudinal studies (measuring at two time intervals to determine the change in biomass over time) or chronosequence studies where stands of known age are measured and then used to determine a rate constant from an assumed time zero.
  Problems: Accurate measurement of stand characteristics requires a very large number of field observations and accurate determination of height/diameter and mass relationships, and accurate determination of belowground biomass is extremely time-intensive.

- **Soil Sampling.** Soil samples of known diameter and depth are collected and analyzed for C content. Bulk density measurements are used to convert mass-based concentration data to a mass of C per unit area. Rates are again determined by longitudinal or chronosequence studies.
  Problems: Soils, and particularly subsoils, have very high variability in C contents. Statistical studies of soil C variability in samples from common soils occurring on the Southern Research and Outreach Center in Waseca, MN, indicate that between 5 and 29 samples for the 0-15 cm depth and 23-222 samples for the 30-60 cm depth are necessary at each sampling period to determine a 10% increase in soil organic C with 95% confidence (Adams, 1984). Few studies are backed by such a rigorous sampling scheme, which also decreases our confidence in their results. Forest soils typically have even higher variability, requiring even more intensive sampling. Thus, measurement of small changes in large C stocks with high variability requires large sample numbers (and hence high costs) to estimate with any statistical confidence and these measurements are sensitive to sampling depth choice. Additional challenges include accurately measuring bulk densities, separating fine roots from soil organic materials, accounting for erosional movement of soils, and even determining where the "surface" is in soils with rough surfaces, notably plowed fields.

- **Micrometeorological Methods**. These methods directly measure fluxes of CO_2 between the atmosphere and the plant/soil surface utilizing atmospheric CO_2 contents and atmospheric eddy velocities. They utilize towers of known height above the canopy; the radius of the area of measurement is approximately 100 times the height of the tower above the vegetative surface.
  Problems: Micrometeorological methods are very expensive compared to the other techniques, require a high level of technological sophistication to run, and require continuous monitoring for long periods to determine net annual fluxes.

- **Modeling Methods**. These methods use complex mathematical models of transfers of C between plants, soils and the atmosphere. They are based on a variety of known or estimated relationships and have the capacity to estimate C sequestration rates for a wide array of conditions.
  Problems: Like all models, their results are only as good as the data and relationships on which they are based. Since many of these relationships are either based on or verified by the results of the types of studies cited above, they generally suffer from most of the same problems that the above methods do.

In estimating rates of C sequestration upon land use or land cover change, it is important to distinguish between changes in C stocks and changes in C sequestration rates over time. Knowledge of the size of C stocks in plant biomass or soils gives no information about the rate at which that C accumulated. To determine rates of accumulation, several additional pieces of information are necessary: 1) the initial C stocks before land conversion, 2) the time since land conversion and 3) the pattern of C accumulation over time following conversion.

If the pattern of C accumulation is linear through time, then it is valid to measure accumulated C stocks, subtract them from initial stocks prior to conversion, and divide by the number of years since conversion to determine a C sequestration rate. There are several approaches that are commonly used to determine linear C sequestration rates. Longitudinal studies are ideal, in which soil and plant C stocks are measured prior to conversion and then again at some point following conversion. However, because of the time scales involved, these studies are often not feasible to establish *de novo* and thus must rely on archived samples or data that may or may not be available. A common alternative approach is to make paired comparisons, for example between row crop agriculture and restored grassland or forests with the assumption that cultivated lands adjacent to restored lands represent the initial conditions prior to conversion, which may or may not be true. In both longitudinal and paired comparison studies, if only two time points are represented, then the rate of C sequestration is most often assumed to be constant over time.

Estimating C sequestration rates becomes more complicated when the rate of C sequestration changes through time (i.e., when the pattern of C accumulation in stocks over time is non-linear). For example, the rate of C sequestration often slows as the time following afforestation or reforestation increases and forest stands mature. In this case, accurate estimates of C sequestration rates cannot be obtained from a change in C stocks over a single time period. Indeed, C stocks may continue to increase even while the *rate* of accumulation slows. In the case of non-linear changes in C stocks, longitudinal or chronosequence studies with fine temporal resolution are necessary to establish the pattern of C accumulation over time and thus how C sequestration rates change. Longitudinal studies of sites are ideal, but if they are not feasible, chronosequences can be used that include multiple sites that vary in their time since conversion. These approaches are powerful because they allow researchers to establish the pattern of C accumulation over time and thus how the rate of sequestration changes. However, the “space-for-time” substitution approach involved in chronosequence studies necessarily assumes similarity among sites with respect to starting conditions, environmental factors, and management, as well as prior land use.

5. Expressing certainty around C sequestration data

The data and interpretations presented in this report are based on a comprehensive and critical review of existing scientific literature on the subject. Because the sequestration rates associated with specific land use practices are highly dependent on climate, we restricted our data collection to studies conducted on sites with climates that are reasonably similar to those of Minnesota.

For all of the land use practices studied, the scientific literature provides a range of C sequestration rates. This variability among rates is a product of several factors, including regional and temporal variations in climate; differences in soils among sites; experimental, sampling and analytical designs used in the studies; and other unknown factors. Because of this variability, we have used statistical analyses to generate the best (i.e., most probable) estimates of values for C sequestration rates in MN. In addition, we provide several statistical measures of the certainty associated with the data.

In this report, we have averaged the estimates of C sequestration rates from existing studies to come up with a mean rate of C sequestration for each land use or land cover change considered. Along with the mean, we present indications of two different types of certainty associated with that mean. First, we present three quantitative statistical measures of the dispersion of data around the mean value (Table 6.1, Fig. 6.1): the standard deviation, the coefficient of variation (the standard deviation divided by the mean multiplied by 100) and the 90% confidence interval (the range of C sequestration rates within which the true mean rate has a 90% chance of falling). Along with these quantitative estimates of statistical certainty, we also provide a semi-arbitrary level of certainty scale based on the coefficient of variation, where high is <40%, medium is 41-80% and low is >81%.

The second type of certainty is related to the probability that a C sequestration rate is actually positive (greater than zero). For example, if the studies synthesized for a particular land use/land cover change include some values that show C loss and some that show C sequestration, then there is little certainty that the practice effectively sequesters C, as C losses are just as likely to occur. In contrast, if the studies synthesized for a particular land use/land cover change all show positive sequestration rates, then there is high certainty that the change actually sequesters C, even if the statistical variability associated with the mean is high. Consequently, we provide a qualitative indication of the certainty that each land use/land cover change leads to a C sequestration rate greater than zero based on the range of values among studies and the confidence interval generated from them. We urge readers to seriously consider both types of certainty indices when using the mean C sequestration rates presented in Table 6.1 of this report. Additionally, other sources of uncertainty that are not possible to express in quantitative terms are discussed for each land use/cover change. These include such things as a lack of studies in Minnesota, a small number of studies, limited sampling within studies, and the like.

The potential quantity of C sequestered by any land use/management practice can be estimated by multiplying the sequestration rate associated with that practice by the area of land involved. The net C sequestration potential associated with conversion of lands from one practice to another can be estimated by determining the difference between the two sequestration rates (rate for new land use practice minus rate for old) and multiplying the resulting "difference" rate by the area involved. Uncertainties associated with sequestration rates are carried through these calculations and should be considered in estimating the total quantity of C sequestered. For example, if a land use conversion has a mean C sequestration rate of 1.0 metric tons per acre per year, the 90% confidence interval ranges from 0.40 - 1.60 metric tons acre^{-1} yr^{-1}, and 1,000 acres are converted to the new land use practice, then the 90% confidence interval for total C sequestered would range between 400 and 1,600 metric tons yr^{-1}. Although the mean (1,000 metric tons yr^{-1}) is our best estimate of the total quantity of C sequestered, there can obviously be large uncertainty about that figure.

6. Carbon sequestration potential of land use and land cover change

The use of land and resources to support the needs of a growing society has rapidly affected the cycling of C between the biosphere and the atmosphere. The increase in atmospheric CO_2 concentration has occurred at unprecedented rates because of anthropogenic activities (IPCC 2007). Strategies to offset the increase in atmospheric CO_2 can be achieved only with improved understanding of the C sequestration potential associated with different land use and land cover (i.e. vegetation composition) changes. Changes in land use and land cover potentially increase C sequestration if they increase plant biomass production and/or decrease rates of detritus or soil organic C decomposition (Lal, 2003).

Here we provide estimates of C sequestration rates associated with changes in land use or land cover for the state of MN (summarized in Table 6.1). The data synthesized here were obtained from the available literature and are based on empirical studies conducted in MN and other locations with comparable climatic and soil conditions and from analyses of existing databases (e.g., the USDA-Forest Service Forest Inventory Analysis database [FIA]) (Appendix II). Modeling studies were excluded from these analyses because there is no feasible way to determine their accuracy.

The estimates presented below (in g C m^{-2} yr^{-1} and metric ton C or CO_2 $acre^{-1}$ yr^{-1}) represent an average of C sequestration rates provided in each selected study. When values of C sequestration rate were available for multiple sites or forest stands within the same publication we considered each value as a unique observation ($n = 2, 3, \ldots, i$). Conversely, when C sequestration rate was presented by authors as a mean (average) value for multiple sites or stands, we considered the mean to be a single observation ($n = 1$). For most land use/land cover conversions, we assume that C sequestration rates will be linear for at least 50 years. One exception is conversion to short-rotation woody crops, where the rotation length is typically less than 50 years. More information about data collection and sources of variability specific to each land use/cover change are provided in each of the following sections.

Interpretation of the provided estimates should take into account the variability, and hence the level of certainty, associated with those figures. Therefore, we recommend that the reader refer to chapter 5 of this report for detailed information concerning the statistical variability associated with C sequestration rates.

Table 6.1 Estimated changes in C sequestration rates upon land use or cover change for the state of Minnesota. Estimates are means of all studies with standard deviations (SD) among studies within a land use/land cover change category, except where noted.

Sector		**Land use/ cover change**	**Estimated C and CO_2 sequestration rate upon land use/cover change^**					
			Total biomass	**Soil**	**Sum**	**Level of Certainty**		
			metric ton C $acre^{-1}$ yr^{-1} ± SD (*n*) *(90% confidence interval)*			of the mean rate[£]	that C sequestration > 0	metric ton CO_2 $acre^{-1}$ yr^{-1} ± S.D.*
Wetland	a	Peatland restoration	0.2 ± 0.1 (5) *(0.1 – 0.2)*		0.2 ± 0.1	Medium	Very high	0.7 ± 0.4
	b	Prairie pothole restoration	N.A.	1.2 ± 1.9 (27)[$] *(0.6 – 1.9)*	1.2 ± 1.9	Low	Very high	4.5 ± 6.9
Forestry	c	Annual row crop to forests	1.3 ± 0.5 (11) *(1.1 – 1.6)*	0.2 ± 0.1 (7) *(0.1 – 0.2)*	1.4 ± 0.5	High	Very high	5.5 ± 1.8
	d	Annual row crop to short-rotation woody crops	1.5 ± 0.6 (5) *(0.9 – 2.1)*	0.4 ± 0.4 (2) *(-1.2 – 2.0)*	1.9 ± 0.7	High	Very high	7.0 ± 2.6
	e	Increased forest stocking	0.2 ± 0.3 (29)[$] *(0.2 – 0.3)*		0.2 ± 0.3	Low	High	0.8 ± 1.0
Agriculture	f	Annual row crops to Pasture/hay land		0.1 ± 0 (3) *(0.1 – 0.2)*		High	High	0.4 ± 0.1
	g	Annual row crop to perennial grassland		0.4 ± 0.4 (24) *(0.3 – 0.6)*		Low	High	1.6 ± 1.6
	h	Conventional to conservation tillage		0.1 ± 0.1 (16) *(0 – 0.1)*		Low	Very low	0.3± 0.5
	i	Inclusion of cover crops in row crop rotation		0.2 ± 0.1 (4) *(0.1 – 0.3)*		Medium	High	0.6 ± 0.3
Perennial Grassland	j	Low diversity to high diversity grassland		0.1 ± 0.4 (4) *(-0.4 – 0.5)*		Low	Very low	0.1 ± 1.39
Urban	k	Turfgrass to urban woodland	0.24 ± N.A. (1)			Low	Very high	0.9 ± N.A.

[^]Estimates refer to a timeframe of ca. 50 yr, except for short-rotation woody crops where estimates apply only to the duration of the stand rotation.
[£]Based on coefficient of variation (CV): CV<40% -High; CV 41-80% - Medium; CV >81% - Low.
[*]Total C sequestration rate converted to CO_2-C equivalent by multiplying by 3.67.
[$]Mean, standard deviation and confidence interval values were estimated by linear regression of: row b) chronosequence data from a single study including many sites; row e) differences in biomass C accumulation between insufficiently and well-stocked forest stands in response to stand age (for stands <30 years).
Lower-case letters refer to sections in text; *n*, number of studies; N.A., not available.

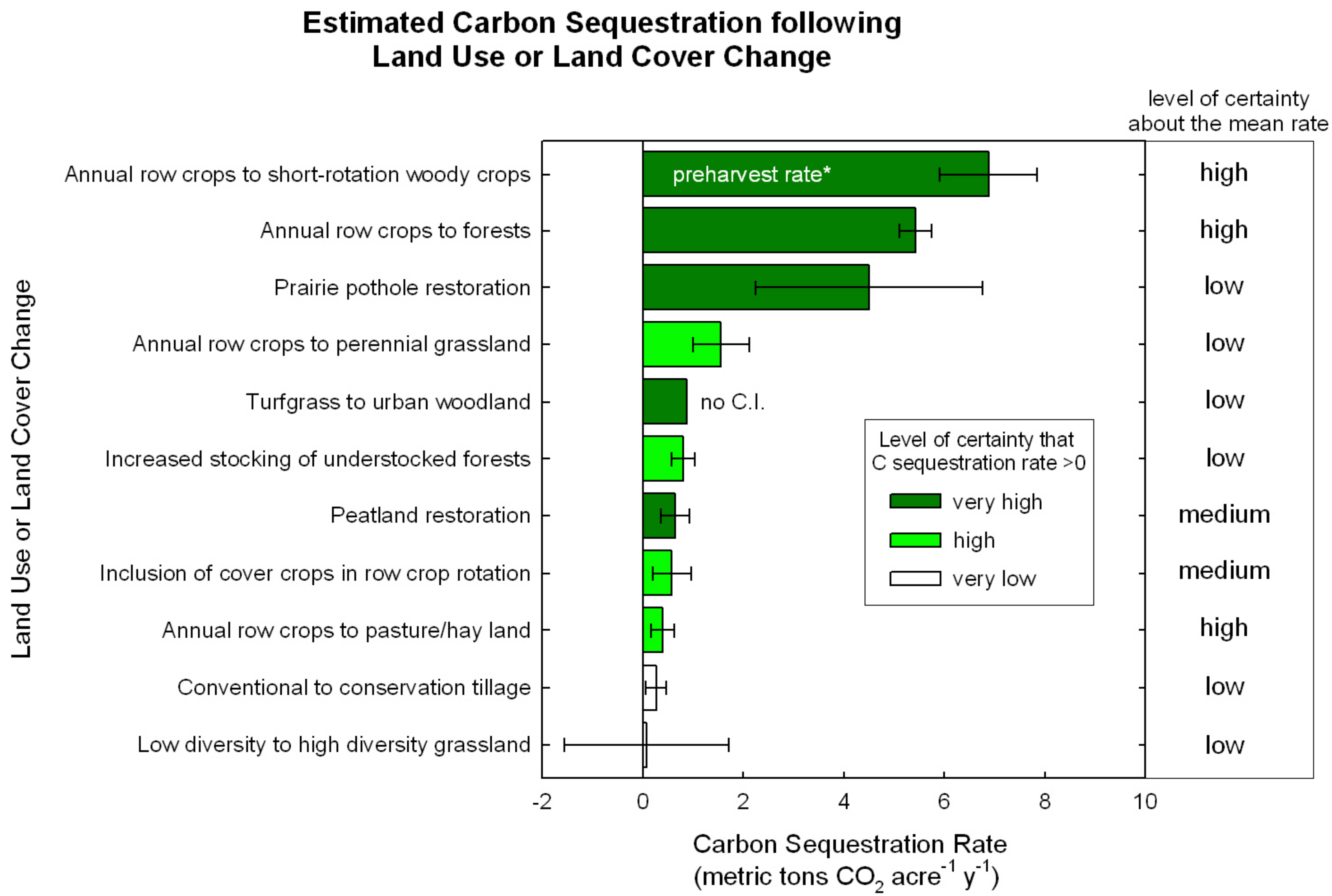


Figure 6.1. **Estimated C sequestration rates associated with land use or land cover changes**. Bars show 90% CI (confidence interval) unless there was only a single study (*n*=1, hence the CI cannot be calculated). *Actual rate will depend on rotation length, C losses during harvest and fate of harvested products.

a. Peatland restoration

Peatlands store large quantities of C that can be depleted rapidly if they are drained (Moore et al., 1998). Restoration of peatlands has been proposed to reverse this process and to prevent further C losses from these ecosystems (Fig. 6.2). Wetlands may also be constructed in one area to mitigate or offset the loss of wetlands in another location due to construction of roads, buildings, or other structures. Peatlands support diverse vegetation, from mosses to sedges to shrubs to trees, depending on site and climatic characteristics. Peatlands are typically considered net C sinks (Gorham, 1991). Despite the enormous importance of peatlands in sequestering C, there is a dearth of measured data concerning changes in C sequestration upon restoration (Roulet et al., 2007). For this reason, the estimates we present are derived not from restored peatlands, but from the analysis of C sequestration rates in undisturbed peatlands from North America and Canada. 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. Thus, application of these estimates to predict potential C sequestration in restored peatlands should be done with caution. Further discussion of uncertainties associated with such an application is presented in section 6.a.iii.

i. Changes in carbon sequestration rates following conversion

Peatlands are estimated to sequester C at a rate of 0.2 metric tons C $acre^{-1}$ yr^{-1} (Table 6.1). Because of the sampling methodologies associated with these types of studies, this estimate includes accumulation of C in both vegetation biomass and soil (Fig. 6.2).

ii. Factors potentially influencing carbon sequestration rates

Climate – Low temperatures reduce aboveground biomass production but generally also decrease decomposition rates (Blodau, 2002). Hence, peatlands at cold sites can accumulate large amounts of C in soil over long time periods. Analysis of peatlands across temperature gradients shows that, in general, greater C sequestration rates occur with increasing temperature, likely because of greater plant productivity. Many climate change scenarios predict that large regions of the country may became both warmer and drier due to reduced precipitation and/or increased evapotranspiration (Lafleur et al., 2003). If these changes lead to a lowering of the water table in peatlands, significant C loss may occur in the near future (Moore and Knowles, 1989).

Drainage- High water tables and limited drainage favor C accumulation in peatlands because of the establishment of anaerobic conditions (Gorham, 1991). Eddy covariance techniques of whole-ecosystem CO_2 flux studies across multiple seasons have shown that peatlands can be a sink for C during wetter periods and a source of C during dry periods (Shurpali et al., 1995; Lafleur et al., 2003), further highlighting the importance of hydrology and water table height in peatland carbon balance.

Vegetation type – Presence of woody vegetation increases C sequestration in aboveground biomass (Blodau, 2002). The recalcitrant nature of some of the mosses and other plant species commonly found in peatlands increases the long-term accumulation of C in soil since these materials are resistant to microbial decomposition (Freeman et al., 2001a, b).

Time- Peatlands accumulate C at a relatively slow rate (Bridgham et al., 2006) compared to many other land uses. However, peatlands often can continue to accrue C for millennia. Most Minnesota peatlands have been accruing C for about 5,000 years. For this reason, assuming all other conditions constant, time plays a key role in C sequestration. Consequently, sites with greater productivity are likely to accumulate C more rapidly under conditions of slower decomposition (e.g. anaerobiosis).

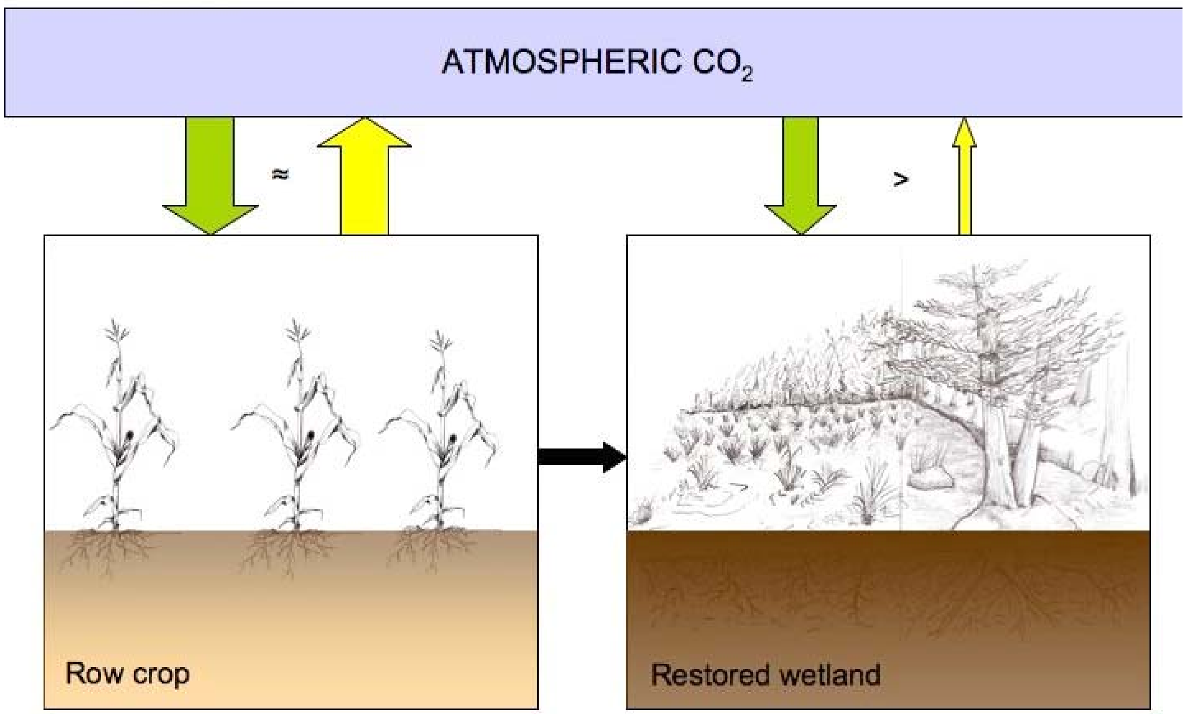


Figure 6.2. Changes in C sequestration over time upon land use change from annual row crop to peatland. Green arrows represent C uptake by plants, yellow arrows indicate C released back to the atmosphere (plant and soil respiration and harvested products), and the sizes of the bar are a relative indication of the sizes of the C flows. Darker soil (brown) color indicates C accumulation in soil. Net C sequestration occurs when green > yellow.

iii. Uncertainties

The estimate presented is uncertain because it is based on data from peatlands that have developed naturally over thousands of years, rather than on data from restored peatlands. Estimates of C sequestration based on radiocarbon analysis of peat cores assume linear C sequestration over time (Gorham, 1991), which may not be a valid assumption. It does, however, put some bounds on the overall rates of C sequestration in peatlands. Alternatively, eddy covariance studies of CO_2 flux over several seasons show that over relatively short time scales, peatlands can vary between being a sink and a source of C because of the effects of interannual climatic variations on C cycling. Therefore, future C sequestration potential in peatlands on decadal timescales will largely depend on future changes in climate and hydrology at a specific region. Notably, none of the studies used for our estimates were located in MN. More accurate estimates of the potential for peatlands to sequester C require development of research sites in MN.

Uncertainties also arise in relation to methane (CH_4) and nitrous oxide (N_2O) emissions from restored peatlands, particularly those in regions where agricultural drainage containing N fertilizers may flow into wetlands. Emissions of CH_4 and N_2O are of particular concern because these gases are much more effective greenhouse gases than CO_2. On a per weight basis, CH_4 is 72 times more effective as a greenhouse gas than CO_2 and N_2O is 289 times more effective over a 20-y time horizon (IPCC 2007). Some studies suggest that the overall C sequestration rate in peatlands will offset the net greenhouse gas emissions of these two gases, but we still have a poor understanding of this matter (e.g. Euliss et al., 2006).

Fertilizer and in particular N runoff may occur when peatlands are restored adjacent to agricultural fields. Because of the distinctive hydrology and vegetation cover of peatlands, studies have shown variable responses of C decomposition following nitrogen addition (Keller et al., 2005; Bubier et al., 2007) and in some cases most of the N added is rapidly lost through denitrification. Establishing grasslands as buffers between the agricultural fields and peatlands may serve to overcome this problem and ensure that peatlands continue to sequester C at current rates.

b. Prairie pothole restoration

Prairie pothole wetlands are extremely productive ecosystems with great potential to sequester C. Although prairie pothole restoration has been suggested as an important potential contributor to C sequestration in many regions in North America (Knutsen and Euliss, 2001), few studies have attempted to quantify the C sequestration potential of these systems. Our estimate is based on a chronosequence-based study (Euliss et al., 2006) that used multiple sites spread across the prairie pothole region (ND, SD, MN, IA). The chronosequence included different 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 in this report, as we assume that C sequestration in plant biomass will saturate relatively quickly (within a few years) in these and similar systems dominated by herbaceous vegetation. Notably, all studies were conducted in recently restored wetlands (2 to 12 yr old). Thus the time period over which these restored wetlands will exhibit positive C sequestration rates is unknown.

i. Changes in carbon sequestration rates following conversion

Restoration of prairie potholes is estimated to sequester 1.2 metric tons C $acre^{-1}$ yr^{-1} in the soil.

ii. Factors potentially influencing carbon sequestration rates

Carbon sequestration rates in prairie potholes may be dependent on the vegetative species used in the restoration efforts, the amount of nitrogen fertilizer that drains into the wetland from agricultural runoff, the depth of water in the wetland once drainage has been eliminated, the duration of the period of saturation, and the intensity of seasonal fluctuations in the water surface height in the pothole (Rosen et al., 1995; Hogan et al., 2004; Euliss et al., 2006; Voldseth et al., 2007). Again, the net effectiveness of C sequestration from prairie pothole restoration in offsetting CH_4 and/or N_2O emissions is poorly understood (Euliss et al., 2006) but is of concern.

iii. Uncertainties

There is still a poor understanding of the effects of biotic and abiotic factors on C cycling in restored prairie potholes. Although restored prairie potholes appear to sequester C rapidly following restoration (Follet et al., 2001), C content is still lower than that of undisturbed wetland sites a few years after conversion (Galatowitsch and van der Valk 1996). There are no data indicating a likely timeframe for full C recovery in restored sites in different regions. Changes in climate are expected for the near future; however, there is still poor understanding of how changes in temperature and precipitation affect C sequestration in prairie potholes. A large amount of C appears to accumulate in biomass (Galatowitsch and van der Valk, 1996; Galatowitsch, 2006) early in the restoration process, but this may vary across regions depending on plant species composition. Regardless, it will likely reach a maximum in a relatively short period of time, given the primarily herbaceous nature of the vegetation. There is a need to extend the analysis to specific regions with distinctive climatic and site characteristics in order to accurately predict rates of C sequestration in these highly productive systems. Further, the establishment of longer chronosequence studies will be useful in understanding the temporal pattern of C sequestration following restoration of prairie potholes.

c. Annual row crops to forest

The rate of C sequestration increases upon land use conversion from annual row crop agriculture to forests (Table 6.1, Fig. 6.3). The terms afforestation and reforestation refer to the establishment of forests at sites that have never been forested and the reestablishment of previously forested sites, respectively. The studies used to determine the estimates provided here 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 of 11 (total biomass) and 9 (soil) samples. At these sites, conversion to forest occurred between 10 and 90 years before sampling, with an average of 54 years. For the studies that measured changes in belowground biomass, the mass of coarse roots averaged 16 % of that of aboveground biomass. Hence, for those studies where only aboveground biomass was reported, we assumed the contribution of coarse roots to be an additional 16% of aboveground biomass.

The sequestration rate presented here derived from the paired comparisons of reforested and adjacent agricultural lands is higher than other estimates of forest C sequestration that have used forest inventory databases from Minnesota (FIA Database, USDA Forest Service) and C stock computer packages (Carbon Online Estimator, COLE 1(b) Report for Minnesota). Forest inventories include a wide range of forest types, including under-stocked and poorly developed sites. Therefore, C sequestration rate estimations based on C stocks of existing forests likely underestimate C sequestration rates that occur with well-managed afforestation and/or reforestation conversions that typically maximize stocking and productivity.

i. Changes in carbon sequestration rates following conversion

The mean C sequestration rates for afforestation in former agricultural soils are 1.0 to 1.5 metric ton C acre^{-1} yr^{-1} in conifer and deciduous forests, respectively. These values come from study sites averaging greater temperatures and precipitation than MN. Colder and drier conditions present in MN can lead to lower rates of C sequestration, but given the small number of studies it is not possible to quantify the magnitude of this decrease in rates.

Soil C sequestration rates are on average 0.2 metric ton C acre^{-1} yr^{-1} in conifer and deciduous forests. Therefore, the total C sequestration rate of afforestation in MN (biomass and soil) is approximately 1.4 metric ton C acre^{-1} yr^{-1}.

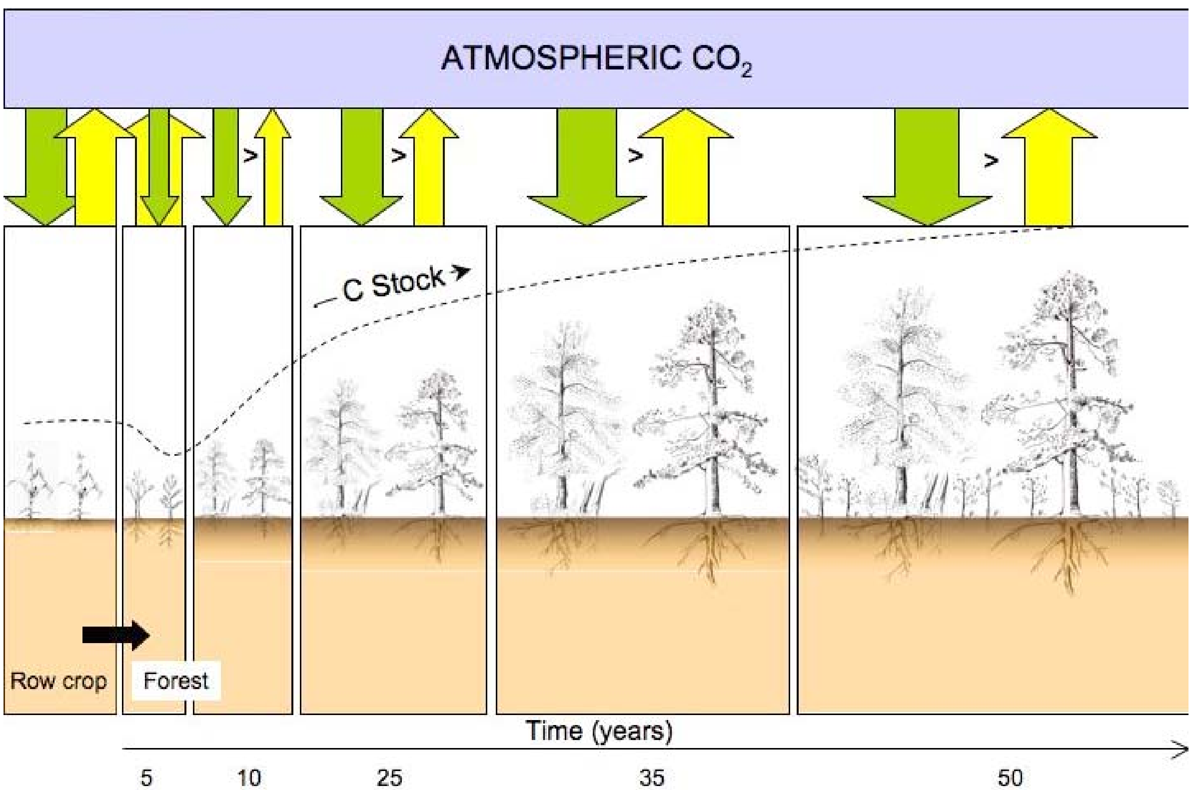


Figure 6.3. Changes in C sequestration over time upon land use change from annual row crop to forests. Green arrows represent C uptake by plants, yellow arrows indicate C released back to the atmosphere (plant and soil respiration and harvested products), and the sizes of the bar are a relative indication of the sizes of the C flows. Darker soil (brown) color indicates C accumulation in soil. Net C sequestration occurs when green > yellow. The dashed line indicates the relative size of the total C stock in vegetation and soils.

ii. Factors potentially influencing carbon sequestration rates

Years since conversion – Initial loss or limited gain of C has been reported in the first 5 to 10 years of forestation and typically is followed by a rapid increase in C sequestration (Hansen, 1993). In later stages of stand development, C accumulates more slowly as the sequestration rate declines. The pattern of change in C sequestration rates through stand development largely depends on tree species composition and site characteristics (Compton et al., 1998).

Tree species composition – Studies across ecosystems suggest greater soil C accumulation in deciduous than in conifer forests, with variations depending on site characteristics and species composition (Guo and Gifford, 2002; Morris et al., 2007). Fast-growing species may show greater C sequestration in the early stages of forest development, but slow-growing species likely accumulate greater C stocks (Vesterdal et al., 2002), typically in biomass, during long rotation cycles.

Soil and site characteristics – Nutrient-rich sites generally promote higher rates of plant growth, but it is not clear whether this translates into higher C sequestrations as returns of C to the atmosphere via respiration could also be higher (Berg and Meentemeyer, 2002).

Atmospheric CO_2 concentrations – One of the largest uncertainties estimating the global C cycle relates to the responses of ecosystem productivity to rising atmospheric CO_2 levels (IPCC 2007). Potential responses of forest productivity to future increases in CO_2 will likely impact the C sequestration rates in reforested/afforested lands, but this is highly uncertain because of difficulties predicting future CO_2 levels and associated climate change responses.

iii. Uncertainties

Data on afforestation and reforestation for the state of MN are few and there is a need for chronosequence studies in order to understand changes in C sequestration rate during forest development. The rates of C sequestration potential presented here may overestimate the actual C sequestration potential for some areas in MN, especially those with low productivity due to poor site quality and climatic conditions.

Typically, there is very high variability associated with forest soil C; hence extensive sampling is needed to accurately characterize soil C changes. The effect of the above-mentioned biotic and abiotic factors on C sequestration needs further investigation, in particular how soil and site characteristics influence forest development and hence the temporal pattern of C sequestration. Predictions of C sequestration rates over times longer than average rotation lengths should take into account the fate of harvested biomass to determine whether the large amount of C will be further sequestered after harvesting in secondary products or rapidly released to the atmosphere (e.g. through burning).

d. Annual row crops to short-rotation woody crops

Fast-growing trees are used in short-rotation cycles (typically < 20 yr) for biomass production. Hybrid poplar and willow are the most common species utilized in the northern U.S. (Hansen, 1993; Zan et al., 2001). Estimates of C sequestration rates (Table 6.1) 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. Data synthesized here were obtained from 7 studies, 6 of which measured biomass and 2 of which measured soil C.

The potential of short-rotation woody crops to offset anthropogenic CO_2 emissions largely depends on the fate of 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 (Updegraff et al., 2004; Sims et al., 2006). 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 (Harmon et al. 1999). Hence the long-term C sequestration potential of this type of short-rotation management could be relatively low. We recommend that these factors be taken into account when using the provided estimates for C sequestration rates.

i. Changes in carbon sequestration rates following conversion

Estimated C sequestration rates following conversion of agricultural land into short-rotation woody crops is 1.5 metric ton C acre^{-1} yr^{-1} in biomass and 0.4 metric ton C acre^{-1} yr^{-1} in soil for the duration of the rotation (i.e., without accounting for C losses during harvest or the fate of harvested biomass) (Table 6.1).

ii. Factors potentially influencing carbon sequestration rates

Site preparation – Intense site preparation often precedes the establishment of short-rotation woody crops, causing initial (< 5 years) loss in soil C that is usually counterbalanced by C gain in rotations lasting 10 yr or longer (Hansen, 1993; Grigal and Berguson, 1998).

Site characteristics – Nutrient-rich sites and fine-textured soils typically favor plant growth, resulting in greater plant productivity. In relation to soil and site characteristics, optimal soil moisture for plant growth has a positive effect on biomass production.

iii. Uncertainties

Few studies have investigated soil C accumulation in short-rotation woody crop systems, and these studies often do not control for sources of variation (e.g. sampling depth, time since conversion). Deep tree root systems may redistribute C deeper in the soil profile compared to row crops (Del Galdo et al., 2003), but most studies have investigated soil C accumulation only in the top 20 cm of the mineral soil. Due to the non-linear pattern of C sequestration after conversion, it is problematic to use studies from literature that focus on forest stands of different age to determine C sequestration rates. Also, although these systems appear to accumulate C during longer (> 10 years) rotations, the upper limit of this C sequestration is still unknown. The current uncertainties associated with patterns in soil C sequestration rates during forest development can be greatly reduced by developing chronosequence studies that control for sources of variation.

Belowground biomass accumulation in short-rotation woody crops may be as high as 25 to 100% of aboveground biomass (Tuskan and Walsh, 2001), but this important component has yet to be accurately characterized. Our estimates of soil C sequestration are highly variable in part because of the use of different sampling procedures among studies: one study includes the contribution of roots to the soil pool, therefore resulting in a very high value of C sequestration compared to the other studies (Hansen, 1993).

e. Management of existing forests - Increased forest stocking

About one-half (53%) of forests in MN are not fully stocked (Miles et al. 2007), suggesting good potential for increasing C sequestration rates and total forest C stocks by optimal stocking of poorly stocked forests. We used data of biomass accumulation of forests under different stocking conditions from the USDA-FS FIA data for Minnesota (2005) to estimate C sequestration rates of improving stocking of understocked stands (Table 6.1). 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 management practices such as increased stocking and rotation length are expected to have comparatively lower effects on the soil than on the standing biomass of the forest.

i. Changes in carbon sequestration rates following conversion

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. Optimal stocking of forests in MN results in an increase in the C sequestration rate of 0.2 metric ton C $acre^{-1}$ yr^{-1} (Table 6.1). This corresponds to an increase from 0.06 in insufficiently stocked forests up to 0.28 metric ton C $acre^{-1}$ yr^{-1} in optimally stocked stands.

ii. Factors potentially affecting carbon sequestration rates

Different forest types have different status of stocking and different C sequestration potential (coefficient of variation of 38% among forest types, COLE 1605(b) Report for Minnesota, 2007) so the net effect of forest stocking on C sequestration will depend on type of forest/species being stocked. The distribution of under-stocked forest land in MN also differs with forest-type (Miles et al. 2007). Therefore, the increase in C sequestration with increased forest stocking depends on the area available for stocking in each forest type and their corresponding sequestration potential. For instance, although aspen forests encompass about one third of all forest land in MN, they have relatively low potential for increased stocking (<10% of aspen stands are poorly stocked). Other forest types such as lowland hardwoods (sugar maple, beech and yellow birch) have high rates of C sequestration (up to 0.7 metric tons C $acre^{-1}$ yr^{-1}) and good stocking potential (up to 20% and 60% of stands still show poor and medium stocking), but lower forest area (around 10% of Minnesota's forest land). Some conifer forests (black spruce and balsam fir) show intermediate rates of C sequestration but have strong potential for increased stocking (around 15% and 50% of stands have poor and medium stocking) in a large proportion of Minnesota's forest land (25% of total area). Other conifer forests with species such as white, red and jack pine also have good stocking potential but comparatively lower area and C sequestration potential. Because of these offsetting effects we believe overall increases in C sequestration rates upon stocking of under-stocked MN's forests will not diverge much from the value of 0.2 metric tons C acre^{-1} yr^{-1}.

iii. Uncertainties

The rates of C sequestration of the different stocking categories were estimated for the first 30-years of forest growth (i.e. the period of most rapid biomass accrual in forest stands). Slower growth after 30 years will decrease the rate of C sequestration below 0.2 metric tons of C acre^{-1} yr^{-1}. The magnitude of this decrease will depend on forest type and site productivity. Stocking could be difficult on some sites with relatively low site productivity. Some forest types with low stocking levels, such as black spruce, occur in areas of low productivity and/or high pressure of browsing and insect herbivory, where seedling establishment can be seriously limited. Also, the areas of under-stocked forest can include wetland areas where enhanced stocking is not possible.

Changes in rotation length

Harvest cycles have the potential to affect C stocks because the total C accumulated increases with forest biomass growth. On the other hand, the rate of C sequestration decreases in the latter part of the rotation cycle because forest growth rates diminish with increasing stand age. At 15 years of age, forests in MN have accumulated about 70% of the C present in old-growth forests, at 30 years 80%, and by 60 years up to 95% (COLE 1605(b) Report for Minnesota, 2007). Median stand age in Minnesota is approximately 55 years but 15%, 25% and 50% of MN forests have stand ages below 15, 30 and 50 years, respectively (Forest Inventory Mapmaker 3.0, 2006). Therefore there is some potential to affect forest C stocks and sequestration potential via changes in rotation length. On one hand, increased rotation length can result in prolonged C accumulation and greater C stocks, but, on the other hand, shorter rotations can potentially lead to faster growth and higher annual rates of C sequestration. However, because the life cycle of products (e.g., paper) associated with short rotations are typically shorter than that of products (e.g., lumber) associated with longer rotations, much of that C may be returned to the atmosphere shortly after harvest.

i. Changes in carbon sequestration rates following conversion

Without considering the fate of harvested products, shortening of rotation length can increase C sequestration rates because of the faster growth of young stands. Conversely, lengthening of rotation length can increase C stocks in biomass. Clearly, the overall effectiveness of these management practices for sequestering C from the atmosphere is highly dependent on the products derived from these rotations and their life cycles.

ii. Factors potentially influencing carbon sequestration rates

Increasing the stocking of forests can potentially enhance both C stocks and sequestration rates by increasing the volume of growing wood per area. As with changes in rotation cycles, the magnitude of the increase depends on forest type, site productivity and the fate of harvested products.

Forest type – The time-course of C accumulation with forest age differs among the different forest types in Minnesota. Therefore, increasing rotation length can potentially have different effects on the C sequestration potential of different forest types. In general, hardwood forests, particularly oak forests, can sequester 30-40% more C by extending rotation lengths from 30 years up to 60-90 years. In contrast, some conifer forests have already accumulated up to 90% of below- and above-ground C at 30 years of age (COLE 1605(b) Report for Minnesota, 2007). About two-thirds of forest land in Minnesota correspond to forest types in the latter group, mainly aspen-birch, spruce-fir and pine (particularly jack pine) forests (Miles 2007). These forests can only increase C sequestration about 20% if rotation cycles are extended beyond 15 years, and only 10% if extended beyond 30 years.

Fate of woody biomass after harvest – The use of harvested wood also will determine the final effect of rotation cycles on final C sequestration. Use of wood for pulp and paper (products with a life-span < 5 years, Harmon et al. 1990) will lead to greater C loss than uses of wood for structure and furniture, with considerable longer life-spans (about 200 years, Harmon et al. 1990). Forests with rapid growth that reached maximum C storage at an early age are normally subjected to shorter rotation cycles; therefore, wood products from these forests can have shorter life-spans and greater CO_2 losses to the atmosphere.

iii. Uncertainties

The overall balance between the higher rates of biomass growth associated with shorter rotations and the longer post-harvest persistence associated with longer rotations determines the net C sequestration; however, data are yet insufficient to precisely determine the net effect of extended rotation cycles on overall C sequestration. Most of the uncertainties relate to the fate of harvested wood products under different forest management cycles. First, different forest types can have different responses. Extending rotation cycles in forests with rapid growth will have little impact on C sequestration if harvested wood products are destined to pulp industry with a short life-span, but could have positive impacts if products are long-lived or are used as biofuels to replace fossil fuels. Second, forest harvest techniques and product processing involves a series of steps that cause disturbance and CO_2 release, and produce scrap and sawdust with very short life-spans. Even in forests harvested for long-term storage wood, more than 50% of harvested biomass is released to the atmosphere in a short period after harvest (Harmon et al., 1990). These responses vary across forest types, harvesting methods and wood product fates. Although it is difficult to estimate the balance between biomass growth gains with shorter rotations and postharvest products persistence, it is likely that extending rotations can only increase C sequestration in forest that reached maturity at later ages.

f. 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 (e.g. Franzluebbers et al., 2000). Rates of C sequestration can vary greatly depending on vegetation type and management (particularly manure management), making any estimate extremely complex to extrapolate. Because of the lack of an extensive dataset, our estimate is based on 3 paired comparison studies between pastures or hay lands with adjacent row crops. The studies had different species composition and spanned observation periods from 3 to 20 years. Because of the low number of studies, this estimate should be considered with caution.

i. Changes in carbon sequestration rates following conversion

Estimated C sequestration rate upon the conversion from row crops to pasture and hay land is 0.1 metric ton C acre^{-1} yr^{-1} (Table 6.1).

ii. Factors potentially influencing carbon sequestration rates

Vegetation type – The choice of vegetative cover largely depends on site and climatic characteristics (Kindscher and Tieszen, 1998). Typically, planting species with deeper root systems favor distribution of C in deeper soil horizons (Del Galdo et al., 2003).

Management type (grazing vs. hay) – Although there is insufficient evidence to distinguish the effects of grazing versus harvesting (i.e. haying) on C sequestration, more soil C likely is sequestered in pasture due to greater return of C (and nutrients) to soil. Fertilization, both conventional and organic, increases plant productivity with implications for greater C accumulation in soil (Izaurralde et al., 2000). However, as part (pasture) or all (hay) of the aboveground biomass is harvested in this type of management, this fertilization effect on long-term C sequestration may be minimal if C is mostly allocated aboveground rather than in the root systems. Therefore, the effect of fertilization on soil C sequestration rate may vary greatly depending on species composition and management intensity (Frank et al., 1995; Liebig et al., 2006). Recent findings suggest that while short-term N fertilization may increase rates of soil C sequestration (Lee et al. 2007), long-term intense N fertilization may in fact deplete soil C by enhancing the rate of microbial decomposition of soil organic matter (Khan et al. 2007). Thus, the effects of N on SOC decomposition remain highly uncertain (Fog 1988). Furthermore, C emissions associated with fertilizer production, transport and application likely more than offset increased C sequestration resulting from fertilization (Schlesinger, 1999) and must be taken into account when estimating total net C sequestration in fertilized pasture or hay lands. Moderate grazing (i.e. removal of 50-60% of forage) does not reduce forage production because of limited root dieback compared to intense grazing, although there is no sufficient evidence that total SOC varies between management practices in the long-term (Schuman et al., 1999; Conant and Paustian, 2001).

Climatic conditions – Typically, greater plant productivity rates and soil C sequestration occur in temperate humid locations, while lower accumulation occurs in extremely dry or humid sites, as a consequence of plant responses to climatic factors (Conant and Paustian, 2001).

iii. Uncertainties

Lack of an extensive dataset greatly hinders our ability to predict changes in C sequestration rate following conversion of agricultural soil in pasture/hay land in MN.

The uncertainties associated with the effects of management, biotic, and abiotic factors on C sequestration could be greatly reduced by developing sets of studies that span across ecosystems. In turn, understanding of the duration of these effects is strongly limited by the lack of well-controlled chronosequence studies.

Introduction of grassland species in former row crop soils likely redistributes C through the soil profile (Franzluebbers et al., 2000; Frank et al., 2006) due to the typically deeper root systems of perennial grass species. However, we have limited knowledge of the vertical distribution of soil C because the few studies available are limited to the top 20 cm of the mineral soil.

g. Annual row crops to perennial grassland

The present estimate of C sequestration upon conversion of agricultural row crops to perennial grassland (Fig. 6.4, Table 6.1) 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 in MN and nearby states. The states considered here (MI, IA, WI, KS, NE, ND, OH) encompass the region that was once tallgrass or mixed-grass prairie, and are thus relatively comparable to the state of MN in terms of climatic conditions and land use history.

i. Changes in carbon sequestration rates following conversion

From the analysis of 24 studies, conversion to perennial grassland of former agricultural fields results in an increase in the mean soil organic C (SOC) sequestration rate of 0.4 metric ton C acre^{-1} yr^{-1} (Table 6.1). However, this estimate is highly uncertain - there was enormous variation among studies resulting in a standard deviation among studies equal to the mean.

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 (ca. 5 yr) and appears still to be accumulating C 40 to 60 years after conversion, as shown by comparison with nearby grassland soils that have never been cultivated (e.g. Conant and Paustian, 2001).

ii. Factors potentially influencing carbon sequestration rates with conversion

Vegetation type - Although the data currently available do not allow any definitive conclusion, C sequestration may be enhanced under native C4 grass species (for example *Andropogon gerardii*, *Sorghastrum nutans*, and *Panicum virgatum*) relative to C3 grasses (but see McLauchlan et al. 2006), and this effect may be greater when C4 grasses are used in combination with legumes (Knops and Tilman, 2000; Conant and Paustian, 2001). The introduction of switchgrass for biofuel production also has been observed to significantly increase C sequestration not only in surface mineral soil, but at depths of up to 90 cm as well (Liebig et al., 2005).

Soil characteristics - Soils developed in nutrient-poor sites are likely to show lower C sequestration rates than those in more nutrient-rich sites. Fine-textured soils (i.e., with greater clay and/or silt) likely show greater C sequestration rates than coarse-texture soils (e.g. Jastrow, 1996).

Climatic conditions – Restored perennial grasslands in regions with greater precipitation have greater C sequestration rates than those in drier regions because of higher plant biomass production and greater rooting depth (and hence C accumulation in soil) in wetter climates (Conant and Paustian, 2001). Colder climates favor C sequestration; under warm conditions faster decomposition may offset greater production leading to lower net C accumulation rates in soil.

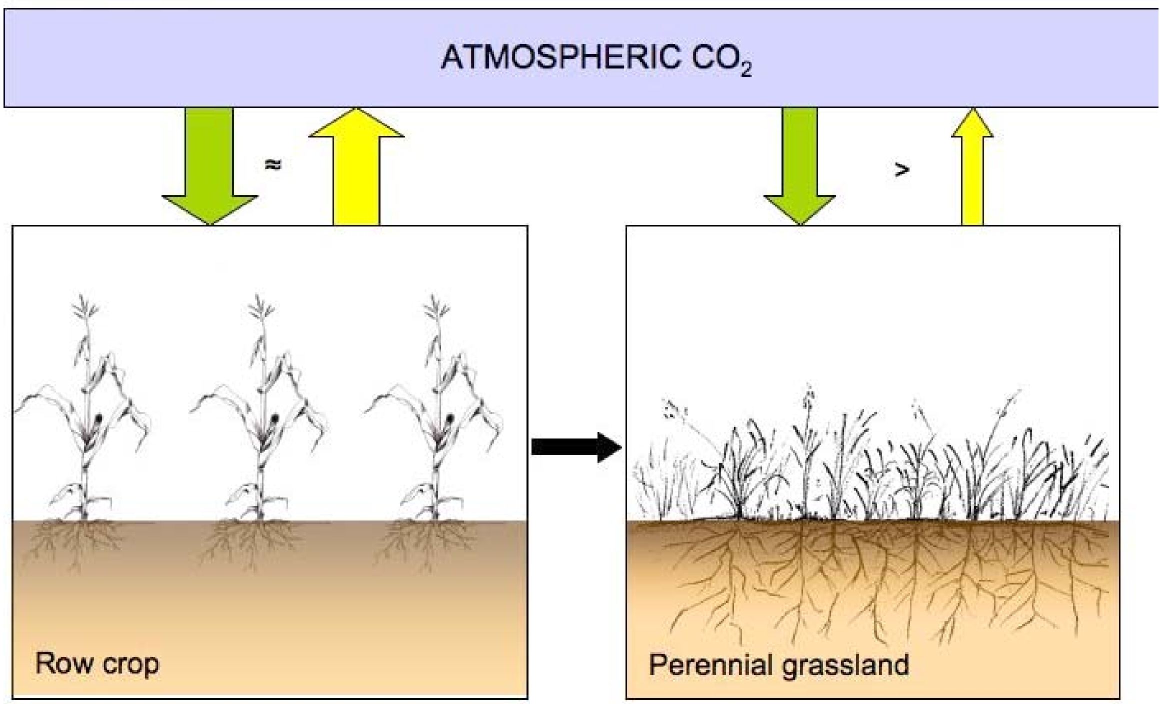


Figure 6.4. Changes in C sequestration over time upon land use change from annual row crop to perennial grassland. Green arrows represent C uptake by plants, yellow arrows indicate C released back to the atmosphere (plant and soil respiration and harvested products), and the sizes of the bar are a relative indication of the sizes of the C flows. Darker soil (brown) color indicates C accumulation in soil. Net C sequestration occurs when green > yellow.

iii. Uncertainties

There is a paucity of data that describe the rate at which SOC sequestration occurs when former agricultural land is converted into perennial grassland in MN. In addition, where data are available, the number of observations is limited, often to only one soil sample per study, further reducing our confidence in these data. In our database there is variability among sites in terms of geographic location, species composition, climatic conditions, and soil characteristics as well as methodological differences such as maximum sampling depth, number of years since conversion and approach (paired sites vs. chronosequence).

Existing chronosequence studies are largely limited to less than 20 yr (often between 5 and 10 yr) since conversion. To describe C sequestration rates following conversion, it is important to gain information on how C accumulation changes over time and how long it takes C sequestration rates to saturate and for C stocks to reach values similar to those of native grasslands.

Carbon distribution in soil can vary greatly through the profile. In plowed agricultural soils the effect of management strongly affects the physical and chemical characteristics of soil, including C, in the top 20 or more cm. Most studies have investigated changes in SOC in the top 20 cm of the mineral soil, and many are limited to the top 5 to 10 cm. More accurate sampling procedures that include deeper soil horizons are necessary to get a better understanding of the potential of perennial grassland soils to sequester C.

Despite the relatively small potential for C sequestration in converted perennial grasslands, additional offset to current CO_2 emissions can derive from the harvest of biomass for biofuel production. An example is that of land under RIM that could be used for this specific purpose.

h. Conventional to conservation tillage

The C sequestration potential associated with the practice of changing from conventional to reduced or no tillage has been investigated broadly, but with mixed and controversial results (Puget and Lal, 2005; Baker et al., 2007). The estimated C sequestration potential provided here (Table 6.1) derives from the analysis of 16 studies conducted in MN and nearby states. Studies conducted in locations with climatic and site characteristics very different from those of MN were not included in this analysis. Despite the relatively large amount of data available, this estimate remains uncertain because of differences in sampling procedure and highly conflicting results among these studies. These results mirror the same sort of conflict observed among studies spread across the nation. The majority of these data were obtained from side-by-side comparisons between sites with conventional tillage and 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. Due to the wide variability in results and the highly conflicting results of these studies, we caution that this should be considered before using this estimate to guide policy making (see section iii. below for more details).

i. Changes in carbon sequestration rates following conversion

The average C sequestration rate associated with the conversion from traditional tillage to reduced or no tillage is 0.1 metric ton C acre^{-1} yr^{-1} (Table 6.1). However, the standard deviation is nearly twice the mean, indicating there is great uncertainty about the actual sequestration rate associated with this change in practice. In addition, the sequestration rates reported in these studies ranged from – 0.12 to 0.24 metric ton C $acre^{-2}$ yr^{-1}. Thus, there is a large uncertainty as to whether the net effects of this change in management practice are negative, positive, or neutral. Studies conducted in MN and NE using micrometeorological methods showed no difference between conventional and no tillage (Baker and Griffis, 2005).

ii. Factors potentially influencing carbon sequestration rates

Carbon inputs to soils are largely controlled by the type of vegetation present and the total amount of biomass produced. Tillage affects where aboveground biomass is placed within the soil horizon. Outputs are controlled by a variety of factors, including aeration (tillage and agricultural drainage increase aeration of the soil), soil nutrient status (high C:N ratios slow down microbial decomposition rates), soil temperature (early season temperatures are typically higher under conventional tillage in Minnesota), soil moisture, soil pH, the nature of the organic materials present (some are more readily decomposed than others), and other factors (e.g. Wanniarachchi et al., 1999).

The net result is a balance between all of these factors. Tillage buries residues deeper in the soil where they are less exposed to aeration than they are at the surface, but it also increases aeration of the upper portions of the soil profile. Nitrogen fertilization increases biomass growth and thus organic matter inputs, but it also may alter microbial decomposition rates in ways that are poorly understood.

iii. Uncertainties

Great uncertainty arises in the estimated value for C sequestration rate because of the lack of data from deep soil horizons (Baker et al., 2007). This is particularly important in view of recent studies showing an overall increase in soil C sequestration in the top 20-30 cm of soil, but a concurrent reduction at greater depths (typically 30-60 cm), with conversion to no-till (Yang and Wander, 1999; Puget and Lal, 2005; Dolan et al., 2005). These findings, corroborated by the analysis conducted here, suggest that the conversion to no tillage may redistribute C in soil, rather than increase overall C accumulation, and that studies that are based on shallow (0-30 cm) sampling depths may appear to measure increases due to no till when, in reality they are only sampling the zone of increase in no-till and ignoring the zone of increase in soils under conventional tillage. Thus they appear to measure an increase due to no till when in fact none may exist. Due to the wide variability in results from these different studies, no consensus exists as to the net effect of tillage on C sequestration rates. There are, however, many other good reasons to promote no- or reduced tillage, including lower fuel usage (estimated to be 1.3 gallons of diesel saved per acre) and reduced erosion. There is a strong need to gather more data from rigorously designed studies that are comparable in terms of sampling procedures and site and soil characteristics. Given the great variability around the data, it is crucial to collect a dataset large enough to detect changes in soil C sequestration.

i. Inclusion of cover crops in row crop systems

Introduction of a winter cover crop into corn-soybean rotations is common in the upper Midwest (De Bruin et al., 2005). These crops are planted in the fall and are typically plowed under or knocked back with herbicides in spring before the main crop is planted. A variety of cover crop species may be included as part of mixed cropping rotations. The use of continuous living cover crops is also currently under investigation as an opportunity to sequester C and to protect the soil from erosion (Lal et al., 1999) and the use of stover as biomass for biofuels production has shown to be promising. Specifically, under this type of practice, a greater amount of stover can be removed without compromising or depleting soil resources. At the same time, biofuels production would improve the currently modest C sequestration potential of cover crops.

The estimated C sequestration rates that occur with the use of cover crops (Fig. 6.5) 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. These studies come from MN and other states in the Midwest and include the use of different species as cover crops. Despite the large interest in this type of land use, only a few studies have compared C sequestration between traditional row crop rotations and rotations that also incorporate cover crops. Thus, this estimate was obtained from the analysis of only 4 studies.

i. Changes in carbon sequestration rates following conversion

The introduction of cover crops is estimated to produce a soil C sequestration rate increase of 0.2 metric ton acre^{-1} yr^{-1} compared to annual row crop rotations that do not include cover crops (Table 6.1).

ii. Factors potentially influencing carbon sequestration rates

Cover crop species – Greater C sequestration occurs in the presence of species with deeper root systems and a more recalcitrant tissue chemistry that slows rates of residue decomposition (e.g. rye) (Ding et al., 2006). Legume cover crops have some additional advantages in that they can fix N (which is typically limiting for plant growth) and may reduce needs for inorganic fertilizer N (Angers, 1992).

Management – Species selection, timing of seeding, fertilization, mowing, grazing, site preparation, irrigation, herbicide applications, and annual climate variations are all factors that may affect soil C sequestration under cover-crop rotations. However, the relative effect of each of these factors is still poorly understood and the few studies currently available have provided mixed results (Ding et al., 2006).

Climate - Extreme climatic conditions (e.g. drought, cold) may reduce crop productivity and survival (Kabir and Koide, 2002), with potential reductions in C accumulation in soil.

Topography – Greater C sequestration occurs in footslope rather than on back slope landscape positions (Kaspar et al., 2006).

iii. Uncertainties

The few studies of C sequestration in cover-crop systems present great variability due to sampling, management practices and environmental conditions, which greatly reduces our confidence in a single estimate of C sequestration rate associated with introduction of a cover crop. While there is widespread agreement that the introduction of cover crops can increase soil C sequestration (Lal et al., 1999), there is insufficient data to describe, both spatially and temporally, the changes in C accumulation rates upon land use change. Also, Minnesota's relatively harsh winter climate limits the choice of winter cover crops, and preference has been given to rye versus other species. Because cover crops may utilize soil moisture early in the growing season that the agronomic crop needs later on, their use in the corn-soybean rotation may be limited in the western, drier portions of the state. More studies are needed that target the effects of common cover crops on soil C sequestration.

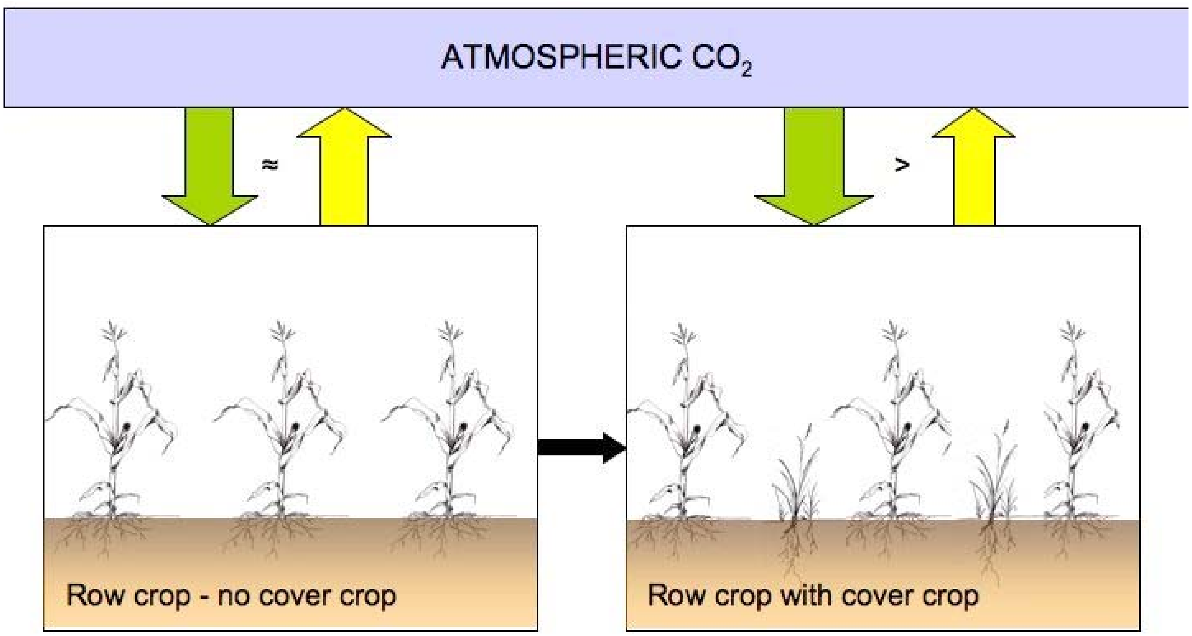


Figure 6.5. **Changes in C sequestration over time upon introduction of a cover crop in annual row crops rotation.** Green arrows represent C uptakes by plants, yellow arrows indicate C released back to the atmosphere (plant and soil respiration and harvested products), and the sizes of the bar are a relative indication of the sizes of the C flows. Net C sequestration occurs when green > yellow.

j. Low diversity to high diversity grasslands

Differences in soil C cycling in grasslands may derive from variation in the level of plant species diversity because of greater resource use and productivity by species-rich mixtures compared to species-poor communities (Spehn et al., 2005; Wang, 2007). A few studies have examined whether species richness affects C sequestration, with some conducted in MN (e.g. Knops and Tilman, 2000). For our estimates we relied on 4 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 (see Appendix II). For these latter two studies, we compared the mean of species-rich mixtures with the mean of grass species monocultures (i.e., we excluded forb monocultures from our analysis). Grass monocultures likely are most representative of present-day low-diversity grassland communities, such as those in set-aside programs or along roadside right-of-ways that are dominated by cool season grasses such as smooth brome, but that could be managed for higher species diversity in the future.

i. Changes in carbon sequestration rates following conversion

Species-rich grasslands are estimated to sequester 0.02 metric ton C acre^{-1} yr^{-1} more than grassland monocultures at similar locations (Table 6.1). However, the standard deviation among 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 studies. Thus, any conclusion is premature.

ii. Factors potentially influencing carbon sequestration rates

Species composition and number – C sequestration likely increases with increasing species number, but the increase likely is not linear and may saturate at a relatively low number of species. Also, the presence or combination of certain species or functional groups of species may enhance C sequestration. For example, C4 grasses in combination with legumes may enhance soil C sequestration over other mixtures (Fornara et al., unpublished). Additionally, diverse mixtures (in comparison to monocultures) are likely to be more responsive (in terms of increased productivity) to future enriched atmospheric CO_2 conditions and heightened N deposition (Reich et al. 2001, 2004) and more stable over time (Tilman et al. 2006); both of which hypothetically could lead to greater C storage in soil.

Climatic conditions – Extreme climatic conditions (e.g. cold, drought) and variation in rainfall during the growing season may be limiting for some species, therefore affecting C sequestration potential of these species (Tilman et al., 2006).

Site characteristics – Nitrogen deficiency is a common problem in plant communities and may limit plant growth. However, this can be overcome by planting N-fixing species, such as legumes, in the mixture. Competition for water resources has been observed in mixed grasslands, hence moisture can greatly affect plant establishment and growth (Caldeira et al., 2001).

iii. Uncertainties

Despite the increasing interest on the ecological effects of plant biodiversity, there are a limited number of studies that investigate differences in C sequestration between low and high species diversity grasslands. More studies across different ecosystems are needed to assess the effects of high diversity grassland on C and nutrient cycling and to understand the effects of environmental variable on plant growth and production. Because of the deep root systems of most grassland species, analysis of C sequestration should include deep soil horizons.

Some variability among current studies occurs because species composition differs across sites, in particular in monocultures. Due to the specific characteristic of each plant species, there is a need to establish research studies using comparable species composition. Finally, much of the uncertainty exists because of the extremely small number of relevant studies and the wide variety of results reported.

Despite the high variability surrounding whether high diversity grasslands will sequester C, the use of biomass for biofuels production could enhance the interest in this type of land practice and further contribute to offsetting CO_2 emissions.

k. Turfgrass to urban woodland

Disturbance associated with urban and suburban development depletes the C stock of areas that were previously cultivated or managed in different ways. However, the establishment of urban forest and other green spaces may in part counterbalance this C loss. Here we present estimates of C sequestration rates in urban forests in MN (Table 6.1). The data derive principally from the USDA for the city of Minneapolis, MN. The estimate considers only aboveground biomass, due to lack of information on and extreme variability of soil C sequestration in urban areas that are climatically similar to MN.

i. Changes in carbon sequestration rates following conversion

Carbon sequestration rates in urban forests can vary greatly depending on tree age and size. In the city of Minneapolis, the estimated aboveground C sequestration rate is 0.2 metric ton C $acre^{-1}$ yr^{-1} (Table 6.1). Because this estimate comes from a single study, we cannot present any estimate of the uncertainty associated with it.

ii. Factors potentially influencing carbon sequestration rates

Vegetation type – Presence of woody vegetation increases C sequestration in urban green areas by storing C above and belowground. Some tree species (e.g. American elm, green ash) show greater C sequestration than others (e.g. blue spruce), hence the choice of vegetation cover can affect the total amount of C sequestered (Nowak et al., 2006). As C sequestration is minimal for small trees, fast growing species may represent an option for more rapid C sequestration. However, slow-growing species typically have longer lifespans and therefore can store more C in standing biomass - even if the C sequestration rate is reduced in old trees- for a longer time than small or fast-rotation trees.

Turfgrass fertilization/management – Intense aeration practices, common in golf courses, may cause a decrease in soil C due to enhanced oxidation (Qian and Follet, 2002). Nitrogen fertilization is common in turfgrass and it appears to increase C sequestration but is associated with C emissions during fertilizer manufacture, transport and application.

iii. Uncertainties

Great variability in C stocks and sequestration rates has been observed across urban areas in North America, depending on urban development, tree size, species composition, and climate (Nowak and Crane, 2002). Therefore, accurate estimates of C sequestration rates in urban forests can be achieved only by conducting measurements in the region of interest. In MN, this is particularly important due to the lack of information on C sequestration upon conversion of agriculture to residential development.

Agricultural to residential

The rapid development of suburban and exurban areas has given rise to conversion of agricultural land into residential land, such that these areas are increasingly dominated by turfgrass and woodland (Golubiewski, 2006). Despite the growing interest in the role of conversion from agriculture to residential development in C sequestration, there are no data available from climatically similar regions that can be used to estimate the effect of this land use change on C sequestration in MN's urban, suburban and exurban areas. More information is needed in view of the predicted increase in residential development at the expense of agricultural or marginal land.

A thorough understanding of the net effect of turfgrass in sequestering C requires that management practices, in particular fertilization and top-soil addition are taken into account due to the large variability in practices and the impact they may have on C cycling and greenhouse gas emissions.

7. Environmental co-benefits of land use/cover and practice change

Many of the land use/land cover practices discussed above provide other environmental services besides the potential to offset CO_2 emissions (e.g. Lal et al., 1999) (Table 8.1). For example, the establishment of perennial grassland or woody vegetation can help reduce runoff and soil erosion, thus reducing sediment and associated phosphorus loads in surface waters. Management of perennial grasslands or forests typically uses far less herbicides and pesticides as compared to traditional row crop management. The presence of multiple grassland species increases ecosystem nutrient retention and the distribution of resource acquisition from throughout the soil profile (Spehn et al., 2005; Tilman et al 2006, Wang, 2007) and can improve soil aggregation and quality. In addition, diverse grasslands increase associated biodiversity and grasslands and forests are important wildlife habitat and provide recreational opportunities.

Among different types of agricultural management, introduction of cover crops and reduced or no tillage in traditional row crop systems also reduce the risk of erosion (Lal et al., 1999). Leguminous cover crops can provide nitrogen inputs to soils and have proven useful for weed control, reducing the need for fertilizer and herbicides, thus improving water quality. However, in some instances both conservation tillage and cover crop practices involve large use of pesticides and herbicides.

Conversion to perennial grassland and short-rotation woody crops can potentially provide further benefits if aboveground biomass is harvested for energy (e.g. biofuels). See also Chapter 9 below for further details concerning C costs associated with this type of management and implications for CO_2 emission offsets. Other land use changes and practices can provide biomass for biofuel production and therefore their potential C sequestration can be greatly enhanced. Among these practices, particularly important are forest and short rotation woody crops products, grassland biomass, and harvested stover from cover crop rotations.

Indirect effects of urban forests on offsetting CO_2 emission derive from the reduced energy use in buildings that are shaded by trees or where trees offer wind protection (Nowak and Crane, 2002; Nowak et al., 2006). Also, a general cooling has been observed in shaded areas compared to areas without trees, thus reducing the urban heat island effect. Urban forests are effective also in reducing air pollution by intercepting gases and particulates (i.e. CO, NO_2, SO_2, O_3, aerosols and particulate matter). Interception of water by trees helps reduce water runoff and flood risk. Additionally, the presence of trees contributes to increased quality of life by improving a city's aesthetic value and increasing property values.

8. Direct and indirect emissions of CO_2 and other greenhouse gases associated with land use/cover change

In this report, estimates of the C sequestration potential of different land use/cover changes are based on the difference in C stocks in biomass and soil between lands prior to and following conversion from one land use/cover to another or between lands in alternative land use/cover categories. Although beyond the scope of this report, a comprehensive evaluation of changes in total net CO_2 sequestration following land use/cover change should take into account other direct and indirect sources of CO_2 and other greenhouse gases that are part of land management practices. Direct CO_2 sources include emissions associated with harvest (e.g. of timber) and use of diesel machinery and vehicles; indirect CO_2 sources include principally emissions from manufacture of fertilizers and pesticides (Robertson and Grace, 2003). While the scope of our study is to investigate the potential of MN land to sequester C, it is important to point out that agricultural practices and other land uses contribute to the emission not only of CO_2, but also of greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) that have great global warming potential (sensu IPCC, 2007). Below we describe the major direct and indirect CO_2 sources associated with common land use practices (summarized in Table 8.1):

Fuel – Every mechanized activity (plowing, planting, harvesting, transporting, etc.) represents a source of CO_2 that derives from the oxidation of C from diesel fuel ($C_{16}H_{34}$) or other fossil fuels to CO_2. One gallon of fuel emits approximately 2,650 g C, corresponding to 9,700 g CO_2.

Nitrogen fertilizer – Production of nitrogen (N) fertilizers alone has been estimated to emit 0.58 mol CO_2 mol^{-1} N produced (IPPC, 1996) and, when CO_2 emissions derived from processing, transportation and application are considered, this value increases up to 1.43 mol CO_2 mol^{-1} N produced (Schlesinger 1999) (or 450 kg CO_2 100 kg^{-1} N applied). Due to this high C-cost, the projected increase in soil C sequestration due to intense N fertilization has been questioned (Schlesinger, 1999). However, positive net C sequestration may be promoted by adopting efficient use of N fertilizer (Izaurralde et al., 2000).

Lime application – Application of agricultural lime ($CaCO_3$ or $CaMg(CO_3)_2$) is typically considered a net source of CO_2 (IPCC 2007) to the atmosphere and indeed CO_2 is emitted to the atmosphere in the presence of strong acids (such as nitric acid). However, under mildly acid, neutral or alkaline conditions, carbonic acid (formed from CO_2 produced by root and microbial respiration) may dissolve lime, resulting in the production of bicarbonate that is leached to ground and surface waters and ultimately exported to the ocean, resulting in the net sequestration of CO_2 from the atmosphere on timescales (i.e., centuries) relevant to this study (Hamilton et al., 2007).

Irrigation – The C costs from irrigation derive mainly from the use of fuel for pumping water; US usage is estimated to total 81 – 304 g CO_2 m^{-2} of land surface area, or approximately 0.33 to 1.23 metric tons per acre (Maddigan et al., 1982). Irrigation in carbonate-rich soils can also cause release of CO_2 when $CaCO_3$ dissolves. Schlesinger (1999) estimates a rate of release of 31 g CO_2 m^{-2} yr^{-1} from irrigation of arid lands.

Nitrification and Denitrification – Nitrous oxide (N_2O) is an important greenhouse gas that can be formed and lost from fertilized agricultural fields due to nitrification and incomplete denitrification. The IPCC estimates that approximately 1.25% of N fertilizer input is lost as N_2O. Consequently, for an N fertilizer application rate of 100 lb N $acre^{-1}$ we would estimate a corresponding flux of 1.87 kg N_2O $acre^{-2}$ yr^{-1}. While this is a relatively small quantity of N_2O, we need to remember that N_2O is much more effective (289 times over a 20-y timeframe) as a greenhouse gas than CO_2. It is estimated that only half of the N applied to crops as fertilizer is actually taken up by plants, with the reminder being lost to the atmosphere (much of that as N_2 gas) or removed via groundwater (Galloway and Cowling, 2002).

Methane - Methane (CH_4) is also an important greenhouse gas. Bacteria in wetland soils as well as in the guts of ruminant animals contribute to CH_4 emissions. Bridgham et al. (2006) provide an estimated annual flux per wetland type after accounting for differences in measuring techniques and temporal variation in different wetlands of the Upper Midwest (four studies in MN and two in MI and WI). This estimate gives the range of CH_4 fluxes from wetlands of 0 to 88 g CH_4 m^{-2} yr^{-1}. Ruminant digestion contributes to about 15% of global CH_4 emissions (IPCC, 2001). Emissions of methane from cattle increase with increasing forage content of their food.

Table 8.1 Major co-benefits derived from land use and land cover changes in terms of both carbon and other greenhouse gases and other environmental factors. Note that land use/land cover changes can have "negative" benefits if, e.g., they increase emissions of other greenhouse gases (CH_4, N_2O), increase need for herbicides or pesticides, or increase use of fossil fuels.

	Carbon and green house gases benefits				Environmental co-benefits				
Land use/cover change	Carbon sequestration	Reduction in fuel consumption	Reduction of other GHG emissions	Production of biomass for biofuel	Erosion/ sediment control	Reduced aquatic nutrient loading	Reduced use herbicide/ pesticide	Improved habitat and biodiversity	Recreation
Peatland restoration	+++	+++	+/-	=/-	+++	+++	+++	+++	+
Prairie pothole restoration	+++	+++	+/-	++	+++	+++	+++	+++	+++
Annual row crops to forests	+++	++	+++	++	+++	+++	+++	+++	+++
Annual row crops to short-rotation woody crops	+++	++	+++	+++	++	+++	++	++	+
Increased stocking of understocked forests	++	=	=	+	=	+	=	+	+
Annual row crops to pasture/hay land	++	++	+/-	+	+++	++	+++	++	+
Annual row crops to perennial grassland	++	+++	+++	+++	+++	+++	+++	+++	+++
Conventional to conservation tillage	+/-	+	+/-	=	++	++	-	=	=
Inclusion of cover crops in row crop rotation	++	+/-	+	++	++	++	+/-	=	=
Low diversity to high diversity grassland	+/-	=	=	+	++	+		+++	++
Turfgrass to urban woodland	+++	++	++	=	++	+	=	+	+++

Legend: Symbols refer to the comparison of each land use/cover change with previous practice, and refer to co-benefits as follow: +++ High; ++ Moderate; + Low; = No difference; - Decrease.

9. Policies and programs affecting C sequestration

This section builds upon the foregoing biophysical section and previous white papers of the Minnesota Terrestrial Carbon Sequestration Initiative. It specifically responds to the legislative mandate to: "evaluate current state policies and programs that affect the levels of terrestrial carbon sequestration on public and private lands and identify gaps and recommend policy changes to increase sequestration rates."[1] It should be noted that even the most optimistic scenario suggests the potential to manage land use/land cover to help meet the state's C emissions objectives is modest; and therefore a focus on land-based C sequestration should not distract policy-makers from the need for more radical changes in other sectors of society to meet the goals of significant long-term reductions in C emissions.

This analysis is based upon three broad goals for managing C stocks and sequestration rates:

1. protect existing C stocks by discouraging land use changes that result in C losses to the atmosphere;
2. enhance and expand terrestrial C sequestration through land use changes that increase the rate or capacity of sequestration; and
3. reduce emissions associated with land use and products.

Programs are also evaluated for their ability to address issues that arise when C sequestration is part of a greenhouse gas reduction effort. These issues include:

- monitoring and verification of sequestration results;
- assurance of long-term security or permanence of sequestered C;
- assurance of positive impacts to local and regional environment and economy; and
- ability to adjust to changing biophysical conditions and information availability

The infrastructure needed for effective terrestrial C sequestration in Minnesota is comprised of a wide array of programs at all levels of government and in the private sector. We have divided relevant programs into four major categories. Within these categories, we identify key existing programs, proposed (but un-funded) initiatives, potential federal partnership opportunities, and gaps where additional attention is needed.

- **Public Land Management** – Millions of acres of forest and wetland are owned and managed by the state. Protecting and enhancing C stocks is not currently a stated management objective on these lands.
- **Government Incentives and Regulations on Private Land** - The majority of land in Minnesota is privately owned. A strong network of conservation programs exists that could be utilized to protect and enhance C stocks.
- **Research, Inventories, and Monitoring** – Infrastructure that could be utilized for the study and documentation of C sequestration.
- **Private Sector Initiatives** –The involvement of traditional conservation partners and new greenhouse gas emissions offset programs in financing sequestration efforts.

[1] Minnesota Senate File 1560 85th Legislative Session 2007/2008

Our evaluation includes a review of information from state agencies, a literature review of professional journals and other publications, discussions with the technical advisory committee of the project and interviews with agency program personnel, non-government organization representatives, and University of Minnesota experts.

The main criteria for program/policy inclusion are:

- **Magnitude of effect** – Policies and programs currently resulting in the sequestration of at least 10,000 metric tons C per year, affecting the management of 10,000 acres of land, or with potential to do so if provided sufficient policy support and resources.
- **Government Level** - This report does not include any programs or policies below the scope of county forest management programs. Federal programs, though significant in effect, are not included.

a. State Government Agencies

The process of implementing a successful terrestrial C sequestration plan for the state of Minnesota may require the cooperation of numerous state agencies. Because the focus of this report is on existing programs, primary attention is given to the Department of Natural Resources, the Board of Water and Soil Resources, and the Minnesota Department of Agriculture. Programs of the Minnesota Department of Transportation, and the Minnesota Pollution Control Agency are also identified.

i. Department of Natural Resources (DNR)

Through its management of state lands and programs for public and private landowners, the DNR strongly impacts C sequestration in Minnesota. DNR manages over 5.5 million acres of land for the State of Minnesota. These lands have been secured for a variety of purposes and are managed with a variety of objectives:

- State Forests (4.5 million acres) are managed for multiple benefits. State forests are working forests that produce nearly one-fourth of the Minnesota timber harvest annually. However, the state forests are also managed to protect ecological resources, provide wildlife habitat and supply a range of recreational opportunities.
- Wildlife Management Areas (1.2 million acres) are managed for the propagation of wildlife and wildlife oriented recreation, particularly hunting.
- State Parks (0.25 million acres) are managed to preserve Minnesota’s natural and cultural heritage as well as to provide a range of outdoor recreation opportunities.
- Scientific and natural areas are managed to perpetuate the ecological diversity of Minnesota's natural heritage for scientific study and public edification as components of a healthy environment.
- Recreational lands such as Water Access Sites and State Trails are managed primarily for recreational uses.
- Private lands programs within DNR provide technical assistance, conservation easements, and cost-share funds for stewardship of natural areas.
- DNR also manages 2.5 million acres of school trust lands and 1 million acres of school trust mineral rights lands to fund public education. Analysis is underway to determine how to increase revenues under sound natural resource conservation and management principles.

ii. Board of Water and Soil Resources (BWSR)
The BWSR is the state soil and water conservation agency, implementing a number of soil and water conservation and wetland protection programs directed at private land. The BWSR works through local units of government, Minnesota's local land use authorities. One of the agency's important roles in C sequestration involves its administration of the Reinvest in Minnesota (RIM) conservation reserve program. They also administer the Wetland Conservation Act that has a goal of no net loss of wetlands within state boundaries. Future programs related to biofuels will also have C sequestration effects. BWSR's continued efforts to promote conservation practices on Minnesota's privately owned lands, and its close relationship with county soil and water conservation districts, will be critical in promoting C sequestration in Minnesota.

iii. Minnesota Department of Agriculture (MDA)
The MDA influences land management through some limited cost share, loan, and incentive programs, but has a greater impact through its technical assistance, educational, and information dissemination programs to landowners. Minnesota's agricultural resources have been identified as critical in increasing C sequestration within the state. Continued assistance provided to farmers and collaboration with other state organizations, such as the Next Generation Energy Board, has consequences for C sequestration.

iv. Department of Transportation (Mn/DOT)
The Department of Transportation has jurisdiction over approximately 175,000 acres of vegetated highway right of way. The primary management considerations for these roadsides are driver safety and roadway maintenance. State statutes encourage management practices that benefit wildlife and improve water quality such as reduced use of herbicides and mowing and increased use of native grasses and wildflowers. To this end Mn/DOT supports the use of Integrated Roadside Vegetation Management (IRVM) practices by its district maintenance personnel. Though C sequestration is currently not a management consideration for Mn/DOT roadsides, many of the above-mentioned practices (IRVM, utilizing native species, reduced mowing), employed by Mn/DOT because of their cost-effectiveness, can have the added benefit of reducing atmospheric C.

v. Minnesota Pollution Control Agency (MPCA)
The MPCA serves Minnesota by examining the quality of the state's environment, developing rules that protect the public's health and the environment, and helping local government, industry and individuals meet their environmental responsibilities. A significant part of the agency's role is to monitor and evaluate the physical, chemical and biological conditions of Minnesota's environment. Finally the agency has a commitment to provide pollution prevention, environmental education, and technical and financial assistance to partners throughout the state. Of particular importance to C sequestration is work to manage methane gas emissions from waste that is stored in landfills and current work on addressing water quality protection and impairments through watershed management such as TMDL planning and implementation. As TMDL's are developed, there

may be opportunities to address water impairments through land management practices that could also sequester C.

vi. County Land Management
Counties control and manage 2.8 million acres of primarily tax forfeit forest land. Minnesota Statute 282 describes the fiduciary responsibilities the counties have in managing their land, but each county creates their own practices and guidelines in meeting those fiduciary responsibilities. Northern county land managers have discussed moving to sustainable forestry certification. These decisions affect C sequestration within their respective counties and ultimately Minnesota.

A note on federal programs:
Millions of acres of public and private lands in Minnesota are managed directly or indirectly under programs of the U.S. Department of Agriculture, including the Farm Services Agency, Natural Resource Conservation Service, US Forest Service, Fish and Wildlife Service; National Park Service; Department of the Interior; Environmental Protection Agency; Bureau of Indian Affairs; and other agencies. Several federal programs dwarf state program resources. A case in point is the USDA's Conservation Reserve Program which affects practices and C stocks on nearly 1.5 million acres of agricultural land. Assessment and recommendations for federal programs is outside the scope of this report except for several federal-state cooperative efforts, such as the Conservation Reserve Enhancement Program, and resource databases.

b. State programs impacting C sequestration

The following Tables (9.1 and 9.2) identify key state programs affecting terrestrial C stocks on both state and private lands and their scope in acreages and average annual funding. They also list the policy tools utilized in each program, including management, easements, grants, tax benefits, research, and technical assistance[2]. The tables also identify related objectives or benefits such as water quality or forest stewardship.

Because of Minnesota's unique historical legacy of substantial state and county forests, and the 50-year commitment to purchasing wildlife habitat through the Wildlife Management Area program, Minnesota has a uniquely large non-federal public land base. This land base is significantly larger than the acreage currently in state-financed conservation projects on private lands that may contribute to C storage.

The DNR clearly has an important role in any proposed C sequestration programs because of the large areas of state lands it manages (Table 9.1). The DNR and county governments manage close to 40% of the forest lands in Minnesota. The DNR management of lands can increase C sequestration through afforestation and reforestation of lands where appropriate, by increased stocking of understocked forest lands, and by protection of C stocks in existing forests. Management increasing productivity can also lead to a higher value forest resource on lands managed for production and could have positive economic impacts. This could be

[2] For public land management activities, the principal policy tool is management.

integrated with current efforts of the recently established Governor's Sub-Cabinet on Forestry, which is working to implement recommendations of the Governor's Task Force on the Competitiveness of Minnesota's Primary Forest Products Industry to maintain and improve forest health and productivity

It is important to note that lands owned and managed by state agencies have, by legislative mandate, specific objectives for their management. For example, the DNR has a policy of multiple use management on lands they administer. Terrestrial C sequestration and protection could be added as one more management goal for those agencies if not in conflict with other management goals mandated by statute.

Table 9.1 State level public land management programs

	Program	Acreage	Funding (average yearly)	Co-benefits
Forest	*DNR Forest Resource Management (SFRM)*	4,500,000	$42 Million	WQ, H, N, E, R
	DNR State Parks (F)	59,060	2.2 million (Parks mgmt budget)	N, E, R
	DNR Scientific and Natural Areas (F)	17,400	2 million (acquisition and mgmt)	H, N, E
	DNR School Trust Lands	2,500,000 (Part of SFRM)	(50% of SFRM Budget spent on School Trust)	H, N, E
	DNR Wildlife Mgmt Areas (F)	720,740	$1,479,439	H, N, E, R
Grassland	*DNR Scientific and Natural Areas (G)*	12,400	$2 Million (total budget including acquisition and management)	H, N, E
	DNR Wildlife Mgmt Areas (G)	103,120	$1,947,930	H, N, E, R
	DNR State Parks (G)	4,623	See Forests	N, E, R
Wetland	*DNR State Parks (W)*	119,418	See Forests	N, E, R
	DNR Wildlife Mgmt Areas (W)	340,068	$1,686,141	H, N, E
	DNR Scientific and Natural Areas (W)	5100	See Forests	H, N, E
Peatland	*DNR State Parks (P)*	14,732	See Forests	N, E, R
	DNR Scientific and Natural Areas (P)	146,600	See Forests	H, N, E

Co-Benefits: WQ=Water Quality, H=Wildlife Habitat, R=Recreation, N=natural heritage, biodiversity, E=education and interpretation, CS=Carbon Sequestration

Source: Information for this table was provided by the DNR.

Public (and private) land management options could be augmented by support for a forest industry that converts wood to durable products that can tie up C for longer periods of time and avoid the emissions represented by shorter lived products. This is another area that could provide further C gains but that requires additional research to define the potential to contribute to reducing C emissions. Increasing market demand for solid wood products could enhance the impact. That demand could be created by state level policies regarding purchasing practices and through public information programs that would also promote the purchase of wood products.

Increasing and protecting C stocks in forests and peatlands have a numbers of environmental co-benefits (see Chapter 7). However, the level of co-benefits from incremental changes in state land management may be moderate when compared to co-benefits associated with changing land use on private lands. State managed lands are predominately in permanent vegetative cover that already provides a wide range of co-benefits. The adoption of C sequestration practices on agricultural or developed lands will generally convey significant environmental co-benefits

Monitoring and Permanence

State managed lands offer advantages over private lands for monitoring of land use practices, verification of C stocks, and protection from conversion. State agencies maintain management plans and inventories of ecological resources and use remotely sensed geographic information systems to monitor resource changes. State managed forests are also certified as sustainably managed which adds third party monitoring and audits, providing another level of verification while also bringing state managed lands in closer accord with existing requirements for registering C credits. Finally, state managed lands have transparent records open to the public which further guarantees reliable monitoring and public oversight.

With terrestrial C storage there are issues related to changing conditions of specific land use practices. Examples include the potential for disease, fire, and fluctuating water tables in wetlands that could alter C emissions from those systems. To adjust to those changes and maintain the stability of stored C will require adaptive management. State managed lands may be more flexible in adapting to those changes due to their greater ability to monitor and respond to changing conditions. In addition, state ownership reduces risk of land conversions that prevail on private lands (unless tied into a perpetual or very long-term contract or easement).

c. Private Land Programs

Seventy-five percent of the land in Minnesota is privately owned. There is an extensive and growing network of government conservation programs, mostly federal, that affects C stocks on private lands. Consideration should be given to including C benefits in the objectives of Minnesota's forest, prairie, and wetland conservation programs. Projects established to address water quality concerns and TMDL regulations could also have C benefits.

Table 9.2 Key state level technical and financial incentives and regulations on private lands (proposed or un-funded programs indicated as "currently unfunded")

	Program	Acreage	Funding (average yearly)	Type of assist.	Co-benefits
Forest	*DNR Forest Stewardship Program*	1,100,000	$1 Million	T	
	DNR Forest Legacy Program	60,000 (87,000 pending)	$40,000 (From Forest Service)	E, T	H, N, E
Urban	*Minnesota Re-Leaf*	NA	$180,000 (very inconsistent since inception)	G	WQ, H, CS
Grassland	*DNR Native Prairie Tax Exemption Program*	16,000	(tax break)	X	N, H
	DNR Native Prairie Bank Program	6,268	$1,000,000 / yr for new easements	E	N, H
	DNR Prairie Stewardship Assistance	(in Prairie Bank)		T	N, H
	BWSR RIM/CREP (G)	64,000	$90,000,000 (total, all cover types)	R, E	WQ
	RIM-Clean Energy			E	
	Minnesota Duck Recovery Plan	*28,000*	*Currently unfunded*	*A, E*	H, WQ, R
Wetland	*BWSR RIM/CREP (W)*	60,000	$90,000,000 (total, all cover types)	R, E	WQ
	BWSR Wetlands Preservation Areas			X	H, N, WQ
	BWSR Wetlands Conservation Act	Protects approx. 13 million acres of MN's wetlands		NA	WQ, H, R, N
	DNR Public Waters Wetlands				H, N, WQ
	Minnesota Duck Recovery Plan	*12,000*	*Currently unfunded*	*A, E*	*H, WQ, R*
AG	MDA Grazing Program	3700	Staff Time	T	WQ
	MDA Ag BMP Loans	2,100,000	Dwight 201-6618	Loan	WQ,

Co-Benefits: WQ=Water Quality, H=Wildlife Habitat, R=Recreation, N=natural heritage, biodiversity, E=education and interpretation, CS=Carbon Sequestration

Types of Assistance: T = Technical assistance; G = Grants; X = Tax exemptions; L = government loans

Increasing funding allotted to existing programs or establishing new programs specifically to deal with C sequestration are options to increase net C sequestration in the state. Table 6.1 of this report identifies land use changes that result in relatively high (and relatively certain) C benefits. Three options stand out in terms of total C sequestered per acre: prairie pothole restoration at 4.5 metric tons of CO_2 $acre^{-1}$ yr^{-1}, conversion of annual row crop lands to short rotation woody crops at 7.0 metric tons $acre^{-1}$ yr^{-1}; and conversion of annual row crop lands to forests at 5.5 metric tons $acre^{-1}$ yr^{-1}. Cover crops are also worth considering due to the potential to convert large acreages relatively easily, the low costs involved, and because this management practice leaves working lands in production. Including the conversion of annual row crop agriculture to perennial grasses is another good option that is consistent and could be leveraged with renewable energy programs

As far as existing plans, The Minnesota Climate Change Advisory Group has set a goal of planting an additional 250,000 acres of forest by 2015 and a total of 1 million new acres of forests by 2025. Such afforestation should cause significant terrestrial C sequestration. As has previously been stated, this goal would have to be integrated with the multiple use management objectives of the DNR which may preclude afforestation in areas important for management of certain wildlife species.

Energy production from agricultural and forest based feedstocks has been fostered by state renewable energy mandates. The governor's NextGen Board is in the process of creating policy and pilot project recommendations. BWSR has been tasked by the legislature to design a RIM Clean Energy program that would provide easements to landowners to convert or maintain landholdings in native perennials with the provision that the landowner would be allowed to harvest biomass from the land for energy and biofuel production. The idea is to create a "working lands" option for landowners that would provide conservation benefits as well as feedstock for energy production. The efficiency of this approach would be increased by direct C sequestration produced by perennial grasses or short-rotation woody crops. The goal of "stacking" benefits" might be achieved by combining biofuel production with C sequestration in marginal areas prone to flooding or erosion, thus also improving water quality.

Co-benefits

Programs that target urban, agricultural, and mined lands have greatest potential for producing significant new co-benefits (improved water quality and flood retention, soil quality, biodiversity, and other benefits). Combining programs that produce biomass feedstocks for renewable fuels and energy with C sequestration, water quality and biodiversity benefits on working lands could lower initial costs of conversion as the landowner generates income from the C sequestering activities. In such a program the state could garner a greater level of public goods.

There is room for providing additional incentives to landowners as well as addressing terrestrial sequestration through regulatory mechanisms. However, there is still the need to develop programs that integrate C sequestration into their objectives and cross-agency coordination in the development of incentive programs to promote land management changes.

d. State and Federal involvement in C inventory and research

Although options exist for enhanced terrestrial C sequestration in the state, there is still considerable uncertainty regarding the capacity of different terrestrial options to sequester and maintain C. That uncertainty lowers the confidence in those management strategies and, in some cases, has eliminated some practices from inclusion in climate change mitigation programs. Research, education and technical assistance will be important in establishing the value of terrestrial sequestration options and building public confidence and support for them.

Because of the co-benefits of many land use practices that promote C sequestration, state investment in research would increase the certainty of our understanding of terrestrial sequestration and the environmental co-benefits generated by such systems. Research is needed to document long-term impacts of adopting options listed in Table 4.1. That research needs to be established on sites that can be maintained and measured for long periods of time. State owned lands including DNR land and University of Minnesota research sites would be the best candidates for such research.

Beyond research, the state needs to develop the capacity to move research results into action through demonstration, education, outreach and technical assistance to landowners to be able to participate in markets for carbon payments on working lands. As programs and/or regulatory mechanisms are developed to promote greater terrestrial C sequestration options, there will be a need for education and technical assistance to help landowners adopt those options. Agencies such as MDA, the Minnesota Extension Service, Soil and Water Conservation Districts, and the DNR can provide valuable assistance with education and technical assistance but will need to be prepared for that. This may be especially important to landowners interested in taking advantage of incentive programs or credits.

Gaps and Information Needs

A number of research needs are apparent, including:

- better research on the C sequestration rates associated with some land use practices, particularly as they related to Minnesota landscapes;
- a full accounting of both direct and indirect (e.g., energy usage, product life cycle analysis) effects of these practices on the net C balance;
- the effects of those options on other important environmental and economic indicators; and
- economic analyses of establishment, maintenance, and verification costs plus opportunity costs for these practices.

There are opportunities to improve funding and value of such research if it can be combined with research that will also quantify additional co-benefits such as water quality, soil quality, reduction of inputs and the production of feedstocks for renewable energy and biofuels.

Table 9.3 Key state and federal research, inventory, and monitoring programs.

	Program	Policy tools	Description
General	USDA-NRCS Natural Resource Inventory	Periodic survey of land use and cover	Longitudinal survey of non-federal lands conducted every five years to assess conditions and trends in soils, water, and other environmental resources.
Forest	DNR Cooperative Stand Assessment or Forest Inventory Management	Inventory of DNR stands	Inventory for forest and wildlife managers that assesses timber species, age, volume, and condition
	DNR - USFS Forest Inventory and Analysis	Inventory under all ownerships	Up to date information for policymakers on forest extent, condition & timber volume, growth, and removals
Wetland	DNR – USEPA Comprehensive Wetland Assessment, Monitoring, and Mapping Strategy	Statewide aerial survey	Randomly selected plots sampled on 3 year rotation to monitor vegetative cover changes in 5 categories (agriculture, rural, urban, silviculture, and natural - forest, prairie, CRP).
Soils	USDA-NRCS Soil Survey	Statewide county surveys	GIS maps and characterization of soil types
	USDA-NRCS STATSGO	Digital maps	Soil survey maps and data on geology, topography, vegetation, and climate assembled with remote sensing images
	MDA Soil Quality Program	Research and monitoring of agricultural practices	Farm-based demonstrations of water quality and profitability improvement of cropping systems, including cover crops, pastures, and tillage systems
Atmosphere	UMN Biometeorology Research	Research facilities	Tall tower observations to collcct high-precision data on carbon fluxes in heavily managed landscapes
	North American Carbon Project	Guidance to policymakers on carbon cycle	The Mid-Continent Intensive Field Campaign (focused in Upper Midwest) tests methodologies for both "top down" atmospheric budgets and "bottom-up" ecosystem inventories
Other	DNR Scientific and Natural Areas	Research and education	Monitors effects of management practices on natural areas and processes, including carbon cycling and global warming
	DNR County Biological Survey	Survey of native plant communities	Collects data for use in protection and management of natural sites
	UMN Cedar Creek	Long term Ecological Research	Field research on effects of elevated CO_2 and other factors on ecosystem function and plant productivity
	Clean Water Legacy	Monitoring land use changes	Multi-agency assessments, implementation, and monitoring of water quality and improvement practices; public outreach and assistance to local implementing agencies

e. Private sector initiatives

There are several opportunities for partnering with the private sector either through traditional conservation organizations and efforts but also through new market-based programs such as the Chicago Climate Exchange (CCX), the Climate Registry; and the new Midwest Cap-and-Trade Program in which Minnesota is a partner (Table 9.4).

The state can benefit from existing programs in other states as well as existing markets but will need to have the capacity to evaluate those different options. There may be advantages to work with existing markets such as the CCX and it will likely be important to look to existing registries and mechanisms for accounting for C credits.

NGOs and private conservation organizations are also interested in C sequestration. Many of these organizations, like the Nature Conservancy (TNC), have traditionally worked closely with government agencies to acquire land for conservation and wildlife management purposes and turn it over to state agencies for management. Similar arrangements may be possible with C sequestration efforts.

Table 9.4 Private Sector Initiatives

Organization	Initiative and Description
Chicago Climate Exchange (CCX)	North America's only active, legally binding carbon credits initiative. Over 21 MMT of CO_2 credits were traded on the exchange in 2007.
Minnesota Farm Bureau	Have teamed with Agragate, a subsidiary of the Iowa Farm Bureau, to aid landowners in enrolling their lands into the CCX.
Midwest Cap and Trade Program – Greenhouse Gas Reduction Accord	An agreement between nine Midwestern states and the Canadian province of Manitoba to create a multi-sector cap and trade program while also agreeing to increase their reliance on renewable energy sources and improved energy efficiency.
Minnesota Farmers Union	As part of the National Farmer's Union program to enroll farmers into the Chicago Climate Exchange's soils offsets program.
The Nature Conservancy	Currently protects more than 300,000 acres throughout the state. These lands are either owned in title by TNC, under a conservation easement or TNC has aided in the payment for the land. TNC has also turned over a hundreds of thousands of acres of land to the state for continued management.
The Climate Registry	Working with member states/tribes to develop and manage a common greenhouse gas emissions reporting system with high integrity that is capable of supporting multiple greenhouse gas emissions reporting and emissions reduction policies.
Recreation Based Conservation Groups	Groups such as Ducks Unlimited and Pheasants Forever have traditionally played important roles in acquiring large tracts of land to be improved and managed for wildlife purposes. This land is then frequently turned over to the state for continued management.

A number of activities are also being developed in the private sector with the objective of sequestering C and providing payments that can be used to institute land use that will sequester C. The Chicago Climate Exchange provides payments for practices that are presumed to produce terrestrial C sequestration, and has supported the development of the infrastructure, guidelines, and controls that would be required of a terrestrial C sequestration market. The recently initiated Midwest Cap and Trade Program will provide an opportunity for the state to enter into a regionally based C market.

In order for Minnesota to compete in the emerging C markets that are becoming national and global, the state and private landowners will have to be able to offer C credits that are reliable, can be monitored and verified and provide confidence to the market that when a credit for a Metric ton of CO_2 is purchased, that amount of C is actually being sequestered and will not be lost back to the atmosphere. To the extent that the state and its private landowners can do that, those credits will have acceptance and greater value in the market. Minnesota has started the process but needs to evaluate options to enter into cap and trade systems for climate change mitigation.

10. Options and opportunities for C sequestration in Minnesota - Scenarios

From the sequestration rate estimates and policy analyses developed in this report, we have developed three scenarios to illustrate the magnitude of terrestrial C losses or gains that might be accomplished. Each of the scenarios has a different emphasis. The first scenario was developed to show potential C losses (CO_2 emissions) that might result from loss of lands with high C stocks (forests, peatlands and prairies). The second scenario shows the potential C sequestration associated with a number of land management changes geared towards producing biomass feedstock for biofuels. The third scenario shows some potential C sequestration gains associated with a combination of potential land use changes. The C sequestration practices used to develop this scenario are those with the highest potential C sequestration rates or those that might involve management changes to large land areas. The acreages of land potentially converted reflect discussions among various members of the Terrestrial Carbon Sequestration Initiative.

These scenarios are meant to be illustrative and do not represent recommendations and should only be viewed as a method of conveying the potential impact of land management conversions. The scenarios are designed to provide a coarse estimate of the magnitude of terrestrial C losses or gains that might be accomplished through land management change. The acreages provided do not represent policy discussions or recommendations, but are simply used to provide a basis for the calculations. These analyses only address the potential for direct C sequestration (or emission) and do not reflect other ecosystem services or co-benefits such as reductions in fossil fuel consumption; erosion/sediment control; reduced aquatic nutrient loading; reduced applications of herbicides, pesticides and fertilizers; improved habitat and biodiversity; and recreation. See Table 6.1 for a ranking of land use changes according to the benefits they can provide. As a terrestrial C sequestration effort takes shape, it will be important to take those co-benefits into account to design a system that can provide the sequestration needed but also the associated benefits.

10.1 Scenario 1 – CO_2 emissions from loss of lands with high C stocks

The first scenario considers CO_2 emissions associated with current annual rates of conversion of forest, peatland and prairie to development and/or annual row crops (Table 10.1). To estimate the total CO_2 emitted as a consequence of conversion of forests and peatlands, we multiplied the annual loss in land area by the C stock in the initial land cover, because a vast majority of the C stock is lost upon conversion. In forests, we considered any land conversion that clears forest biomass (where most of the C resides), mainly for development or for agriculture. In MN there are approximately 16.2 million acres of forests containing around 1,600 million metric tons of C, or approximately 100 metric tons of stored C per acre (367 metric tons of CO_2 per acre, see Chapter 3). In peatlands, we considered losses by mining or any other activity that completely removes the peat (where most of the C resides). A total of 5.73 million acres of peatland in the state of MN contain 4,250 million metric tons of C, or approximately 745 metric tons of stored C per acre (2732 metric tons of CO_2 per acre, see Chapter 3). Because these are one-time conversions these losses must be counted only once and not accumulated on an annual basis. To estimate C losses associated with conversion of prairies, which are mostly converted for use in agriculture, we assumed that cultivated prairies lose C at an annual rate equal and opposite to the rate that row crop agriculture sequesters C upon conversion to perennial grassland (Table 6.1). We then multiplied this annual rate of C loss by 50 years.

Table 10.1 Potential C losses from loss of land with high C stocks.

Land use change	C loss rate (metric tons CO_2 acre^{-1})	Acres converted annually	Total C Loss (metric tons CO_2 yr^{-1})	Total C Loss (million metric tons CO_2 yr^{-1})
Forests to annual row crops or urban	367	5,000	1,835,000	1.84
Peatlands to annual row crops or urban	2,732	1,000	2,732,000	2.73
Perennial grasslands to annual row crops	80	1,000	80,000	0.08
Totals			4,647,000	4.65

10.2 Scenario 2 – Biofuel/Bioenergy Production

This scenario estimates the impact of land management changes geared towards the production of woody or grass-based biofuels **(Table 10.2).**

Herein we limit the land use options to those that have the greatest potential to provide biomass feedstock for fuel and energy from a dedicated source of biomass. Again, this scenario only addresses the direct sequestration of C by these practices and does not account for the sizable impact of renewable fuels on reducing fossil C use and its subsequent effect on atmospheric CO_2 levels. The land use options described in this scenario also provide additional ecosystem benefits, such as improvements in water quality, improved wildlife habitat, and enhanced biodiversity.

These land management changes match well with the options currently proposed for renewable energy. In this scenario, conversion of row crops to forest, short rotation woody crops, and perennial grasslands are considered and described. Additionally, the inclusion of cover crops in corn rotations is also included. While the cover crops themselves would not be directly used for biofuels, they might enable the use of a higher proportion of corn stover for biofuels as pelletized fuels or as feedstocks for ethanol production. Efforts to promote biofuel production could be strengthened by the Farm Bill currently under discussion at the federal level and the RIM Clean Energy Program being developed by BWSR for the legislature.

Table 10.2 Biofuels Production in Agricultural and Forest Sectors

Biofuel options	C sequestration rate (metric tons CO_2 $acre^{-1}$ yr^{-1})	Acreage	Total C Sequestration (metric tons CO_2 yr^{-1})	Total C Sequestration (million metric tons CO_2 yr^{-1})
Annual row crop to forests	5.5	200,000	1,100,000	1.10
Annual row crop to short-rotation woody crops	7	200,000	1,400,000	1.40
Annual row crops to perennial grassland	1.6	100,000	160,000	0.16
Inclusion of cover crops in row crop rotation	0.6	600,000	360,000	0.36
Totals		1,100,000	3,020,000	3.02

10.3 Scenario 3 – Multiple practices scenario

This scenario is the result of discussions with members of the task force and represents a combination of potential land use changes **(Table 10.3).**

Some of the suggested land use changes are based on policies under consideration by a number of state agencies (e.g, the DNR's Duck Plan) or on land use changes that are likely to result in the greatest C sequestration either because of high rates of C sequestration per unit area or because of relatively large potential land area available for conversion. Thus, in combination, they have the potential to offset 3.8% of Minnesota's 2005 (151 million metric tons) annual CO_2 emissions, or 13% of the 45.3 million metric ton reduction target for 2025.

It is worth noting, as is also apparent when reviewing the other scenarios, that many of the current agency and sector strategies and programs to attain conservation, wildlife, water quality, and other environmental goals could be integrated with a state level terrestrial C sequestration program. It is also clear that many of these proposals target the same lands, and that the overall land available for these land management changes is considerably less than the totals presented in Table 8.2. In particular, the potential loss of working agricultural lands and their impact on the state, and particularly the rural, economy should be carefully considered prior to implementation of any programs that may affect land management changes in those lands.

Table 10.3 Multiple land management options

Multiple options	C sequestration rate (metric tons CO_2 $acre^{-1}$ yr^{-1})	Potentially Available Acreage	Total C Sequestration (metric tons CO_2 yr^{-1})	Total C Sequestration (million metric tons CO_2 yr^{-1})	Loss of Working Lands
Prairie pothole restoration	4.5	300,000	1,350,000	1.35	yes
Afforestation	5.5	100,000	550,000	0.55	maybe
Annual row crop to short-rotation woody crops	7	100,000	700,000	0.70	no
Increased forest stocking	0.8	2,000,000	1,600,000	1.60	no
Annual row crops to pasture/hayland	0.4	300,000	120,000	0.12	no
Annual row crops to perennial grassland	1.6	700,000	1,120,000	1.12	no
Inclusion of cover crops in row crop rotation	0.6	600,000	360,000	0.36	no
Totals		4,100,000[1]	5,800,000	5.8	

[1] Note that the total acreage affected by the land use/land management changes proposed in this scenario represents about 7.5% of Minnesota's total surface area.

11. Monitoring program to assess terrestrial ecosystem C sequestration

There are two types of monitoring commonly associated with C sequestration programs. One type is concerned with the accurate determination of the amount of C sequestered by a particular practice over time, and either involves direct measurement/estimation of C in biomass or soils at the start and end of the timeframe of interest or else measures of C exchange with the atmosphere by micrometeorological methods. This type of monitoring is relatively expensive. The second type of monitoring seeks to verify that a specific practice is being implemented at a site, and is usually conducted by visual observation, remote sensing, or other means, and is much less expensive on a per acre basis than the first type. The two types of monitoring are used together to estimate the amount of C sequestered by implementation of practices over a large area. The C sequestration rate (metric tons C $acre^{-1}$ yr^{-1}) is determined by the first type of monitoring and is then attributed to all the acreages that can be verified using the second type of monitoring to estimate the total quantity of C sequestered per year.

This section will focus on the first type of monitoring, that used to estimate the C sequestration rate for a specific practice. Monitoring for verification of practice implementation and maintenance is discussed in Chapter 9.

Monitoring programs typically involve long-term studies over many years (in some cases decades) focused on long-term dedicated sites. Their purpose is to provide a baseline and set of benchmarks for understanding and quantifying changes in important environmental factors that otherwise may be too gradual or too variable to detect.

To be effective, monitoring programs need to be:

- established on representative sites where the practices of interest will be maintained for the duration of the monitoring program;
- designed to provide rigorous, defensible results; and
- funded for the duration of the monitoring program.

The ecological value of monitoring sites is that results are in theory representative, and thus can be used to make predictions over long time frames for large areas that use similar practices under comparable conditions.

The purpose of this section of the report is to provide generic criteria that can be used when developing monitoring programs that aim to quantify net C sequestration rates under different land use practices. General directions for establishing monitoring sites in MN are provided in the following sections, with particular attention given to site selection and experimental design in monitoring C sequestration. However, specific criteria need to be further developed once the particular practices, monitoring methods, and site locations have been selected.

a. Site Selection

Monitoring sites should be located on lands in the public trust. The use of public lands allows for long-term control of the monitoring sites and avoids loss of sites due to unanticipated changes in land use, management, ownership, participation, or other unforeseen events. Examples include University of Minnesota Research Centers, DNR lands, and others.

Monitoring sites should be "representative" of broad areas of the state that may implement the land use practices being monitored. Site characteristics that need to be considered include climate, soil types, slope, and land use history. Other characteristics may also be important for different land use implementations.

Initial site characterization. Sites should be initially characterized for land use history, soil properties and classification, climate, landforms, current vegetation, and soil and/or plant biomass C contents and their variability. In particular, sites selected for monitoring of ecosystem C trends should be characterized for the initial variability in C stocks in the soil or biomass, depending on which is to be studied, as that variability is needed to determine the nature and intensity of future sampling and analytical protocols.

Access and other issues. Monitoring sites need to have adequate access for sampling, instrumentation, and other issues. One important site selection criterion is that sites be adequately protected against disturbances that can alter C sequestration rates, such as fires, vandalism, etc. If sites are to be monitored using micrometeorological methods using eddy correlation techniques, they will also require adequate wind fetch and availability of electrical power to the site.

b. Experimental Design

The experimental design for a monitoring network ultimately determines the overall success of the monitoring effort and its ability to measure and monitor C sequestration. The design of a monitoring program is determined by the analytical methods used (biomass monitoring, soil sampling, or micrometeorological methods), the smallest level of change to be detected, the variability inherent in the C pool being measured, and a variety of other factors.

Given that monitoring both biomass and soil C are likely to involve multiple sites, each with a degree of variability and uncertainty, certain considerations apply similarly to both.

i. Biomass monitoring and soil sampling and analysis

The appropriate type, location and replication of sites for biomass and soil C monitoring depend on the scope of the program and the characterization of the Minnesota landscape to be sampled. Once such criteria are defined, the numbers of sites and samples from which results are obtained need to be big enough to overcome the uncertainty associated with the variability measured both within and across sites. Specifically, the use of the Data Quality Objective (DQO) approach allows one to *a priori* calculate the number of samples that need to be taken at each sampling interval to detect a change of a certain magnitude. This calculation is based on:

- the initial size and variability (i.e., standard deviation) of C concentrations or quantities in the pool (soil, biomass) to be measured;
- the minimum level of change in C stocks one needs to be able to detect;
- the statistical level of confidence desired in the results; and
- other factors related to the specific analyses to be conducted.

The measurement of small changes in large pools having high variability requires a higher number of samples at each sample interval than measuring large changes in pools with low variability and low concentrations. This is an issue for both biomass and soil C monitoring, but more so for the latter because of its inherent high variability.

Other sampling parameters that need to be clearly addressed prior to the initiation of monitoring include, but are not limited to:

- the timing of sampling;
- spatial location and georeferencing of samples;
- potential contamination issues;
- potential analytical issues;
- sample handling, storage and archiving;
- data reporting and storage; and
- statistical design and analyses.

ii. Micrometeorological methods

Micrometeorological methods have been used to monitor whole ecosystem fluxes (exchange between the terrestrial surface and the atmosphere) of C (in the form of CO_2) and other greenhouse gases (GHGs), including N_2O, and CH_4. If one can accurately measure all other losses of C from the system (e.g., biomass harvest, leaching of organic carbon compounds in drainage waters) or else can safely assume that they are zero, then the use of micrometeorological methods may be warranted. They do not suffer from the problem of measuring tiny changes in large pools, since atmospheric concentrations of GHGs are typically small. Thus, micrometeorological techniques are often able to measure the net effects of a treatment in a single year, whereas several years may be required for a detectable change to occur in soils or biomass. However, gas fluxes are dynamic enough that any single year is not considered sufficient or representative of a single site. Due to annual variability in fluxes, paired systems are generally used to study differences in C sequestration between two or more different treatments or management practices, rather than comparing one year's data with another. Unfortunately, the drawback of the system is the sizeable cost; unlike biomass or soil sampling, micrometeorological measurements can rarely be made at more than a pair of sites in most studies.

Special considerations associated with the use micrometeorological methods for monitoring include, but are not limited to:

- having sufficient fetch (upwind open area) for eddy currents to develop and be representative of the field or ecosystem under study;
- availability of reliable electrical power;

- high cost of equipment and implementation; and
- technical expertise required to run them and process the resulting data.

Additionally, determination of net differences in treatments or management practices typically requires constant monitoring over most of the year.

c. Monitoring Carbon

i. in Soil

Monitoring of changes in soil C concentrations requires additional considerations to those outlined above, including:

- depth of sampling;
- measurement of bulk density;
- homogenization of large samples;
- sample size (which affects soil variability);
- compaction of samples in moist finer-textured soils and loss of samples when sampling dry sandy soils;
- removal of roots and/or coarse fragments;
- sample drying; and
- archiving and preservation of samples.

Even such apparently trivial concepts as determining the location of the soil surface in uneven (tilled or forested) terrain needs to be considered in developing a sampling plan. Soil landscape position is also a strong consideration, as soil C contents can vary widely along hillslopes due to differential water movement and erosion. Erosional movement and redeposition of surface soils in annual cropping systems can redistribute more soil C in a year than can be sequestered from the atmosphere, further confounding measurements, particularly if only one landscape position is sampled.

Monitoring C sequestration in existing peatlands over any reasonable time frame is not feasible using soil sampling techniques due to the huge masses of C already present, the large variability in C concentrations and quantities, and numerous other concerns peculiar to sampling peats, including determining the location of the surface (it can vary by more than a foot in hummocky peats), the ease with which peats can be compacted, and the extreme difficulty of measuring bulk densities, which can change dramatically with changes in surficial water content. Monitoring of existing peatlands is accomplished mainly by micrometeorological methods, which have their own drawbacks noted above.

ii. in Forest Biomass

Determining biomass sequestration rates associated with management practices on existing forests requires measurement of aboveground biomass C at the initiation of the practice and at some time in the future. The difference between the measurements is, within the error of measurement, the change in biomass C over the period of observation. Measurements of belowground biomass C are extremely difficult to make accurately because of the difficulties inherent in excavating and separating roots from the soil. Belowground biomass C is typically estimated from established relationships with aboveground biomass C, based on studies conducted for that purpose.

Determining biomass C sequestration rates associated with afforestation or reforestation of lands not currently in forest vegetation is typically easier as the initial biomass value can often be considered to be zero.

Considerations:

- Soil C monitoring in afforestation/reforestation practices is subjected to the same considerations previously noted. In particular, because of the action of deep roots of trees, soil sampling in forests should include deeper soil layers.
- Biomass C is estimated in forests normally via allometric relationships that are based on extrapolations of biomass allocation indices among different plant parts and their C contents. These indices show significant variation across climatic regions, soils and forest types. Therefore, the accuracy of biometric estimates needs to considered when determining overall sources of variability in biomass measurements.
- One particular case of allometric extrapolations is the estimation of belowground biomass growth and C sequestration. The variability of belowground biomass estimates across different climates, soils and forest types should also be considered when estimating C sequestration of afforested/reforested land. Because of the difficulties of measuring belowground stocks in a large number of areas, this information can be inferred from the literature.
- Forest management practices, such as stocking, changes in rotation length and thinning need to be considered in order to increase representativeness. As noted before, monitoring the effect of these practices on C sequestration in established forests would require greater precision than in afforestation/reforestation in order to detect changes in C stocks.
- Perhaps more than in any other land type, forest C sequestration rates strongly depend on forest type, soils and climate; therefore monitoring should consider the main representative forest areas in the state. Because of the span of forests in Minnesota this can be a difficult consideration to fulfill.
- Despite concerns regarding any single measurement, existing inventory programs, in particular the US Forest Inventory Analysis, represent an enormous ongoing monitoring effort that should be linked with in developing any Minnesota-centric forest C monitoring work.

iii. in other biomass types

Other biomass types of concern are materials that may increasingly be grown for biofuel, and include a variety of grasses and forbs. Sequestration rates are typically measured directly by weighing or otherwise measuring the harvested biomass and determining its C concentration on a per unit mass basis prior to its conversion to fuel.

12. Demonstration sites

Demonstration sites differ from monitoring sites both in the purpose for their establishment and in their operation. Demonstration sites are mainly educational tools, whereas monitoring sites are measurement tools to determine the response of ecosystems to various land management practices or to verify that certain practices are being implemented. In the context of a C sequestration program, demonstration sites would be established to show land owners, consultants, agency personnel, and others how to establish, manage, and maintain specific or new land use practices with which they are unfamiliar. For example, sites might be developed to demonstrate how to establish and maintain biologically diverse grasslands on steeply sloping, erodible lands or to show landowners how to increase tree stocking rates in under-stocked forest lands. Demonstration projects can also used to model how different partnerships can work together to implement a project or program.

While some demonstration sites might also be suitable for the mutual establishment of a monitoring site, it is likely that more demonstration sites would be established than monitoring sites due to the intense *a priori* site characterization, frequent and intense sampling intervals, and overall high costs required to establish and maintain rigorous monitoring sites. In addition, demonstration sites should be located such that they are accessible to the land owners and managers in the target audience.

Because many of the land use practices that are known to sequester C are already promoted for other ecological services they may provide (e.g., erosion control, enhanced wildlife habitat), it makes sense to build on existing outreach and education efforts targeting these same land use practices and to collaborate and coordinate with organizations already promoting them, including the Minnesota Extension Service, state agencies, Soil and Water Conservation Districts, and the Regional Sustainable Development Partnerships.

Generic criteria for establishment of demonstration sites include access for the target audience, development of rigorous economic analyses of the establishment and maintenance of the land use practice, promotion of associated environmental co-benefits, and coordination with organizations promoting those benefits.

a. Site Selection

Demonstration sites should be located on lands controlled by the state, university, or cooperating land owners. Demonstration sites should clearly be located within the area of interest for the land use practice being demonstrated, and should be within relatively close distance of land owners who may be interested in adopting the practices. An ideal network of sites would be well-distributed throughout the region of applicability to maximize accessibility.

Other characteristics of importance include having facilities for reasonable public access at (usually scheduled) intervals. Having on-site areas for display of information would be an added bonus.

b. Design and Operation

Demonstrations should be accomplished using land management techniques and equipment similar to that currently used by local land managers where possible. Land owners and managers will be much more willing to adopt land use practices if they can clearly see how they can establish and manage the lands with a limited investment in new equipment.

Extensive, rigorous economic analyses should be conducted at each demonstration site to clearly show the costs and benefits of proposed land use changes. This requires the participation of economists in the early, planning stages of the project so that the economic analyses are integral to the design of the projects and not just an added afterthought.

Results of C sequestration measurements from the most representative monitoring sites can be used to estimate the potential C sequestration of demonstration sites.

c. Education and Outreach

Efforts should be made to utilize existing education and outreach efforts. Collaborative arrangements should be made with existing or proposed efforts by the Minnesota Extension Service, Minnesota state agencies, NGOs, the Regional Sustainable Development Partnerships, and cooperating federal agencies such as the USDA-Forest Service, the USDA-National Resource Conservation Service, and the USDA-Agricultural Research Service. In particular, where C sequestration practices are associated with other environmental co-benefits (such as erosion control or enhanced wildlife habitat), collaborations among agencies, NGOs, and others can be leveraged to also promote the C sequestration benefits of these practices along with the existing messages regarding the other environmental co-benefits. Additional efforts should be made to advertise and promote these efforts through print, broadcast, and particularly online media.

13. Conclusions and recommendations

This report has shown that a variety of land use and land cover changes and management practices can be used to enhance terrestrial C sequestration, the process by which C is stored in vegetation and soils. The magnitude of enhanced terrestrial C sequestration likely will be modest (likely a few percent of present emissions from fossil fuel combustion) and difficult to verify because of the high degree of variability in terrestrial C stocks, particularly in soils. Furthermore, the rates of C sequestration for some land use and land cover changes remain highly uncertain. Nevertheless, in part because many of the land use and land cover changes discussed here confer additional environmental benefits, policymakers should consider a three-step approach for incorporating terrestrial C sequestration into Minnesota's climate protection efforts: 1) protecting existing large C stocks in peatlands and forests, 2) strengthening policies to promote those land use and land cover changes that sequester significant amounts of C, and 3) establishing monitoring and demonstration programs to reduce uncertainties and to assess the amounts of C sequestered over time.

Recommendation #1: **Preserve the existing large carbon stocks in peatlands and forests by identifying and protecting peatlands and forests vulnerable to conversion, fire, and other preventable threats.**

Discussion: Peatlands and forests in Minnesota contain very large C stocks, estimated to be exceed 4 billion metric tons and 1 billion metric tons of C respectively. Release of this C to the atmosphere as CO_2 can result from human activities such as peatland drainage and forest conversion (e.g., from urbanization or agricultural expansion), and could increase in the future because of drought stress related to climate change, wildfire, insect pests, and disease. Such a release would accelerate global warming and require greater reductions in CO_2 emissions elsewhere. A large percentage of Minnesota's forest and peatland resources are in public domain and can be protected through programs at the Department of Natural Resources. Applicable programs on private land include Forest Legacy Program, Native Prairie Bank, Wetlands Preserve Program, and Wetlands Conservation Act, as well as land protection programs managed by numerous private conservation organizations.

Recommendation #2: **Promote those land use and land cover changes that are most certain to cause C sequestration by including them in local, regional, and statewide conservation, renewable energy, and sustainable development priorities.**

Discussion: This report indicates that there is a wide range in the magnitude and certainty of land use/cover effects on C sequestration. At one end of the spectrum, the rate of C sequestration is relatively large, and certainly greater than zero, for conversion of annual row crops to forests and short-rotation woody crops, and for restoration of prairie potholes. These three are the most promising, on a per acre basis, in terms of sequestering substantial C. Conversion from annual row crops to perennial grassland, with 25 to 35% of the sequestration potential per acre of those listed above, is the next most promising, although the certainty about the mean rate is relatively low. Positive rates of sequestration likely will also result from increased stocking of understocked forests, peatland restoration, and conversion of turfgrass to urban woodland, but rates are only about half that of conversion to perennial grassland; moreover the level of certainty regarding those rates ranges from medium to very low for the latter. Incorporation of cover crops into row crop agriculture and conversion of annual row crops to hayland or pasture would both very likely lead to modest, but positive rates of C sequestration. And for two land use/cover changes, conversion from low-diversity to high-diversity perennial grassland and from conventional to conservation tillage, it is unknown whether conversion actually results in C sequestration as opposed to C loss.

A useful approach to increasing terrestrial C sequestration in the near term is to incorporate C objectives into broader environmental, economic, and renewable energy programs, with an emphasis on those land use or land cover changes that have typically the highest sequestration rates and as well medium to high certainty regarding whether sequestration rates are greater than zero. For example, perennial biofuel systems present a particularly attractive opportunity for reducing fossil fuel emissions while increasing soil C, and contributing to local economies and environment. Urban forestry could be another important strategy for combining sequestration, energy efficiency, and environmental values, although the magnitude of C sequestration (while undoubtedly positive) is unknown, but probably small. Numerous public and private programs to improve water quality, flood protection, forest productivity, and biodiversity could be reformed to increase C benefits at little additional cost including many programs at the Department of Natural Resources and the Board of Water and Soil Resources.

Recommendation #3: Invest in monitoring and demonstration programs in order to build public, practitioner, and investor confidence in terrestrial C sequestration as a viable emission reduction strategy.

Discussion: A major conclusion of this report is that protecting and enhancing the state's C stocks is an important resource management strategy needing research and education to be implemented successfully. However, given the uncertainty surrounding rates of C sequestration following land use/land cover change, the state should undertake a program to establish 1) monitoring sites for quantifying C sequestration rates of different land use/land cover conversions and 2) demonstrations of land use/land cover changes that are most promising in terms of C sequestration. Such a program will increase public confidence in the viability of terrestrial C sequestration to contribute to Minnesota's emission reduction targets. Monitoring sites to quantify the C sequestration rate associated with particular land use/cover conversions should be established on public lands and sites should be representative of the relevant regions of the state for particular land use/land cover changes. Demonstration projects should be established to demonstrate to relevant land owners, land managers, and policy makers how particular land use/land cover changes could be implemented and maintained. Financial investment in monitoring and demonstrations must be sufficient that changes in C stocks over long periods of time can be determined with scientific and statistical rigor.

Much of the infrastructure needed to research, educate, and deploy successful sequestration techniques already exists in government, education, and private conservation organizations. Building this capacity through expanded private-public partnerships to finance demonstration projects may be a particularly attractive investment strategy given the widely recognized co-benefits of many sequestration practices.

Appendix I – Peatland inventory

The Minnesota DNR Peat Inventory[(1)] estimates that there are 2,621,780 acres of peatland containing 1,932 million metric tons of C in Aitkin, Lake of the Woods, Beltrami, Koochiching, and St. Louis counties. Using these data, we searched the STATSGO database for the same organic soil mapping units used in the DNR report and found an additional 1,546,794 acres of those same soil series in the remaining 78 counties in the state. The total C content of these soils was estimated from their areal extent, the depth of the typifying pedons as reported in the USDA-NRCS NASIS database, an assumed bulk density of 0.21 g/cm^3, and an assumed C concentration of 58% in the peat. These calculations estimated an additional 1,152 million metric tons of C stored in the peatlands identified in the database. However, these two calculations only accounted for 4.17 of the total 5.73 million acres of peatland reported in the LMIC land cover data (Table 2.1) due to two factors. The first is the lack of identification of other organic soils. There are numerous other organic soil series present in the state, many of which have a somewhat limited areal extent. Secondly, the STATSGO soil maps have a fairly coarse resolution and simply do not recognize many inclusions, such as smaller peat bogs or fens. Consequently, many of these soil mapping units were simply not identified.

To estimate the C content of the approximately 1.56 million acres of peatland not identified in our analysis, we assumed the remaining acres of peatland had similar C contents per acre as the ones identified, and therefore extrapolated our results to produce an estimate of 4,250 million metric tons of C in peatlands in Minnesota.

[(1)] Downloadable from url: http://www.lmic.state.mn.us/chouse/metadata/peatmaps.html

Appendix II – C sequestration rates in biomass and soils

C sequestration rates in plant biomass and soil for alternative land use/land cover change categories by sector, including data form all individual studies used to obtain mean estimates presented in Table 4.1. Where studies presented estimates from more than one location (site, forest stand, etc.), we included each as an individual observation. Mean sequestration rate (SD) among observations is presented for each category preceding presentation of data from individual studies. SD, standard deviation among observations.

Land use/land cover change by sector	Location	Time since conversion	Max. soil sampling depth	Dominant plant cover	C sequestration rate			Source
					Total	Biomass	Soil	
		Yr	*Cm*		*g C m⁻² yr⁻¹*			
Wetland								
Peatland restoration	**Mean (SD)**				**45 (20)** [a]			
	Ottawa			Moss and shrubs	60 [a]			Moore et al. 2002
	U.S.			Bog, mosses	25 [a]			Gorham et al. 1991, 2003
	Ottawa			Moss and shrubs	68 [a]			Lafleur et al. 2001, 2003
	U.S.			Various peatland spp.	48 [a]			Armentano & Menges 1988
	Ottawa			Shrubs, sedges, moss	22 [a]			Roulet et al. 2007
Prairie pothole restoration	**Mean (SD)**						**305 (N.A.)**	
	ND,SD, MN,IA	<5	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 & Lal 2005
Annual row crops to short-rotation woody crops	**Mean (SD)**				**372 (154)**	**97 (93)**	
	Central US	12 to 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 to 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	Tall grass prairie		390	Al-Kaisi et al.2005
	NE	10	5	Tall grass prairie		58	Baer et al. 2002
	MI	10	50	Mixed native		79	Degryze et al. 2004
	IA,MN	7 to 9	20	Mixed grasses		-27	Follet et al. 1998
	NE	6	20	Mixed grasses		94	Follet et al. 1998
	ND	10	20	Mixed grasses		59	Follet et al. 1998
	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	Tall grass prairie	70	Jastrow 1987
	MN	6.5	7.5	Mixed	22	Karlen et al. 1999
	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 & legumes	20	Knops & Tilman 2000
	WI	12	5	Native prairie	25	Kucharik et al. 2003
	WI	4 to 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 & legumes	109	McLauchlan et al. 2006
	Central US			Mixed grass	40	Sperow et al. 2003
	IN	8	100	Tall mixed grasses	210	Omonode & Vyn 2006
Conventional to conservation tillage	**Mean (SD)**				**19 (33)**	
	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 & Griffis 2005
	MN	13	30	Corn	-8	Clapp et al. 2000
	Ontario	25	60	Corn-soybean	42	Deen & Kataki 2003
	MN	23	45	Corn-soybean	0	Dolan et al. 2005
	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 & Shipitalo 2004
	OH	8	80	Corn-soybean		50	Puget & Lal 2005
	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							
	Mean (SD)					**5 (95)**	
Low diversity to high diversity grassland	ND	3		Prairie vs. Wheatgrass		20	Frank 2002
	IN	6 to 8	100	Tall grass mixed spp. vs. Switchgrass		-131	Omonode & 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 & unpublished
Urban							
Turfgrass to urban woodland	**Mean (SD)**				**240 (N.A.)**		
	MN			Various tree spp.	240		USDA Report 2006

[a] Values are cumulative C sequestration rates
[b] Root contribution calculated as 16% of aboveground biomass
[c] Includes root biomass
N.A., not available

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