Biophysical Aspects of Terrestrial Carbon Sequestration in Minnesota

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Abstract

Many land-use practices have the potential to sequester atmospheric carbon as biomass and soil organic carbon. The objective of this paper is to assess which terrestrial management practices will provide the best sequestration opportunities for Minnesota landscapes as a basis for a carbon trading market. This literature review focuses on management practices that have the potential for adoption over a sufficiently large areal extent of Minnesota where a significant quantity of carbon can be sequestered. We investigated the following practices as having sufficient potential carbon sequestration rates and applicability to Minnesota ecosystems: the use of cover crops in row-crop agriculture, conversion of row-crop acreage to grasslands or pasture, restoration of wetlands, use of reduced or no-till systems, afforestation of agricultural land and agroforestry. A scoring system based on criteria developed to assess the applicability and confidence of the data reviewed was used to obtain a weighted average of carbon sequestration for a management practice. Many land management strategies that might have the potential to sequester atmospheric carbon do not have experimental evidence to support their carbon benefit. Future research initiatives must focus on describing carbon dynamics of management systems such as grazed pasture systems, bioenergy crops, restoration of farmed wetlands, cover crops, and windbreaks. Management systems that have solid experimental evidence of their carbon benefit in Minnesota include agroforestry, afforestation and grassland set aside in programs such as CRP.

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Introduction

Carbon-trading programs and carbon markets are based on trading credits for carbon sequestered by specified practices for carbon emitted by a source in excess of an emissions cap. Identifying management practices that dependably sequester atmospheric carbon is the foundation for the establishment of a carbon-trading program.

A carbon market is a program that allows members to reduce their greenhouse gas emissions through partnerships with offset projects. Exchangeable allowances are issued to member greenhouse-gas emitters while exchangeable offsets are issued to participants who practice carbon sequestration through forestry and/or agriculture or other practices. Ideally, this collaboration will minimize the total net release of greenhouse gases by members. In order to implement a carbon-trading market that successfully offsets greenhouse gases, the storage rates of atmospheric carbon that the carbon credits are based upon must be accurate. Carbon markets cannot fulfill their purpose of reducing net atmospheric carbon emissions if they are based on inaccurate sequestration rates and, thus, inaccurate offset values.

Many practices have been identified that are thought to store, or sequester, atmospheric carbon in terrestrial landscapes. All of these strategies are based on the ability of green plants to extract carbon dioxide from the atmosphere and to convert it to complex carbon forms, such as sugars, cellulose, and lignins. This process is opposed by processes of respiration, both plant and microbial, whereby complex carbon compounds are oxidized to produce energy and carbon dioxide, which is released back to the atmosphere. Processes that produce net increases in complex carbohydrates are considered to sequester carbon. The sequestered carbon may be stored in standing biomass, particularly in forests where the residence time of carbon in biomass is relatively high, and in soils, where portions of the organic matter may have residence times of hundreds to thousands of years.

A number of forest-related land-use strategies have been suggested for carbon sequestration, including afforestation, both natural succession and managed implementation, fire suppression, suppression of insect infestations, and short rotation woody crop systems (Dixon et al. 1994; Dixon 1995; Post and Kwon 2000; Tilman et al. 2000; Tuskan and Walsh 2001).

Likewise, a number of strategies have been proposed to sequester atmospheric carbon in soils. The carbon content of soils is a type of steady state where inputs are balanced against outputs. Inputs include the addition of organic materials to the soil surface from aboveground biomass, and to the subsurface through the turnover of plant roots and the transport of surficial organic materials below the surface by worms, ants, and other invertebrates. Losses occur through oxidation of organic matter and much smaller losses in drainage waters.

Many soils in the Upper Midwest have lost significant quantities of soil organic matter via enhanced oxidation due to cultivation and drainage. Cultivation on the Great Plains is believed to be responsible for soil organic carbon losses up to 20 to 60% (Gebhart et al. 1994), although this is complicated by significant decreases in organic matter inputs associated with conversion from perennial prairie grasses to annual row crops. Management strategies that increase organic matter inputs or decrease losses by oxidation have the potential to increase organic matter in soils and to sequester atmospheric carbon. Specific strategies proposed to increase carbon pools in soils include increases in cropping frequency, minimizing fallow periods, use of cover crops or permanent living cover with row-crop annuals, increasing crop residues, nitrogen fertilization, decreasing oxidation of the soil through reduced or no-tillage management, the planting of permanent perennial vegetation, and wetland restoration (Euliss et al. 2005; Paustian et al. 1997; Post and Kwon 2000).

The objective of this paper is to assess, as accurately as possible, which terrestrial management options will provide the best sequestration opportunities for Minnesota landscapes as a basis for a carbon trading market. To that end, we have critically reviewed the existing scientific literature on terrestrial carbon sequestration practices and have evaluated those practices for:

- applicability to Minnesota landscapes, climates, and ecosystems; and
- accurate rates of carbon sequestration when applied in Minnesota.

For a carbon trading market to be effective at offsetting fossil fuel emissions, it is essential that the carbon offsets be based on feasible, accurate sequestration rates, not on idealized estimates. Failure to do so may allow greenhouse gas emitters to trade real emissions of carbon for carbon offsets which are, in fact, much lower than assumed, resulting in a far lower reduction of net emissions than intended. This point emphasizes the importance and necessity of accurate, regionally focused data on carbon sequestration rates to serve as the foundation for establishing a carbon credit market.

Methodology

This literature review focuses on management strategies for terrestrial ecosystems that have the potential to sequester carbon. We developed the following criteria to aid in selection of management practices for analysis:

1. One or more rigorous research studies concerning the practice must have been published in the existing scientific literature;
2. The practice must be applicable to Minnesota landscapes, climate, ecosystems, and land-use practices; and
3. The practice must have the potential for adoption over a sufficiently large areal extent of Minnesota such that a significant quantity of carbon can be sequestered.

We investigated the following practices as having sufficient potential carbon sequestration rates and applicability to Minnesota landscapes: the use of cover crops in annual row-crop agricultural rotations, conversion of row-crop acreage to grasslands or pasture, restoration of wetlands, use of reduced or no-till tillage systems, afforestation of agricultural lands or abandoned farmlands, and agroforestry.

A cursory glance at the literature clearly shows that a wide range of sequestration rates are published for specific practices. This is not surprising, considering that these studies were conducted throughout the world on landscapes having different soil, climatic, vegetative, and management regimes. In order to obtain the most accurate sequestration values for practices in Minnesota, we used two criteria to assess the applicability of the results of these studies to Minnesota landscapes and our confidence in the accuracy of the results of the study for the landscape on which it was conducted:

4. Proximity to Minnesota (or similarity in climates, ecosystems, and land uses). Data from Minnesota and the surrounding region were given precedence as being more applicable,

but when few data were available, data from other areas of the United States and Europe were used; and

5. Rigor of the research methodology and data obtained. The methodology of each paper was scrutinized to determine the rigor of the study and the accuracy of the carbon sequestration values reported. In particular, for carbon sequestration in soils, we looked at the study design, numbers of sites, numbers of samples per site, sampling depth, duration of the experiment or study, utilization of stratified sampling techniques incorporating landscape variability, or use of more rigorous research techniques such as micrometeorological methods.

A simple scoring system based on these criteria was applied to the data to obtain a weighted average of carbon sequestration rates.

Practices

Tillage

There are many different types of tillage practices used in agriculture, including conventional tillage, reduced tillage, conservation tillage, strip tillage, and no-tillage. Conventional tillage uses a moldboard plow that turns over the furrow slice, buries the surface soil approximately 6 to 8 inches deep, and leaves less than 10% residue on the soil surface. No-tillage is actually a subset of conservation tillage and, as the name implies, the soil is not tilled by plowing but is only disturbed during planting. This practice leaves more than 30% residue on the soil surface.

Conversion of conventional or conservation tillage systems to no-tillage systems has been widely promoted as a means to sequester carbon in the soil (Bruce et al. 1999; Lal et al. 1998; Lal 2003; Paustian et al. 1997). This hypothesis is based on the concept that minimizing disturbance to the soil will decrease aeration, minimize oxidation of organic matter, promote better aggregation and thus stabilize organic matter into microaggregate structures (Bruce et al. 1999; Paustian et al. 2000; Sperow et al. 2003). Many researchers have concluded that no-tillage systems sequester carbon and have measured sequestration rates between 22 and 85 g C m^{-2} yr^{-1} (Hooker et al. 2005; Karlen et al. 1998; Lal et al. 1998; Six et al. 2004; West and Marland 2002). These studies are based on comparison of soil samples obtained from sites under conventional tillage and under no-till.

However, recent studies based on micrometeorological techniques, which directly measure CO_2 fluxes between the atmosphere and the land surface, show no significant differences in carbon sequestration between similar fields managed with conventional tillage and no-tillage systems (Baker and Griffis 2005; Verma et al. 2005). The results of these studies show that the carbon balance for corn-soybean rotations under both conventional tillage and no-till are either neutral or slightly negative.

Why do these two analytical techniques produce apparently different results when applied to a comparison of the same systems? What is the basis for this difference? A recent study by Dolan et al. (2006) may help answer these questions. Dolan et al. (2006) showed that conventional tillage and no-till stores the same amount of carbon in the soil profile, but the distribution by depth is different for the two tillage systems. They found that, under no-tillage management, the upper 15 cm of soil does indeed store more carbon than conventional tillage. However, this trend is reversed below 20 cm where conventional tillage stores significantly more carbon. Since conventional tillage buries residue to 6-8 inches (15-20 cm), one would expect more carbon at the 20 cm depth under conventional tillage, and this is the case.

A common hypothesis in recent research is that tillage method influences the carbon distribution in the profile which attempts to explain the apparent carbon sequestration in no-till systems (Angers et al. 1997; Deen and Kataki 2003; VandenBygaart et al. 2002; Wander and Traina 1996; Wanniarachchi et al. 1999; Yang and Kay 2001). Dean and Kataki conclude that distribution of soil organic carbon is dependent on tillage implement, and tillage does not affect the total soil organic carbon storage in the upper 40 cm. The research of Wanniarachchi et al. (1999), Wander and Traina (1996), Yang and Kay (2001), and Angers et al. (1997) also conclude that tillage method does not affect the carbon storage potential of agricultural soils, but does influence the vertical distribution of carbon within the profile. Similar research suggests that moldboard tillage stores carbon deeper within the soil profile, and no-tillage systems store more carbon near the soil surface at the expense of deeper carbon storage (VandenBygaart et al. 2002; Yang and Kay 2001).

Likewise, a recent analysis of published literature results by Baker showed that studies comparing the carbon sequestration capabilities of conventional tillage and no-tillage systems utilizing sampling depths of 30 cm or less did, indeed, conclude that no-tillage sequestered more carbon than conventional tillage. However, studies utilizing sampling depths of 40 cm or greater concluded that there was no difference between conventional tillage and no-tillage systems.

These data provide strong evidence that no-tillage does not sequester more carbon than conventional tillage, but rather leads to a redistribution of organic carbon in the soil profile. Differing soil sampling strategies may lead to differing conclusions regarding the impact of tillage on organic carbon sequestration in soils (Dolan et al. 2006); however, those conclusions appear to be an artifact of the sampling scheme involved and not of relative potential differences in carbon sequestration. Therefore, sampling of the entire profile is essential to determining the carbon sequestration potential.

Although, no-tillage systems do provide a number of important ecological services, such as erosion control and water quality benefits, a critical review of the literature to date leads us to conclude that no-tillage systems do not sequester more carbon than conventional tillage systems. Therefore, we cannot recommend the use of no-tillage systems as the basis for carbon sequestration credits or their use in carbon trading markets.

Perennial Grasslands

Prior to European settlement, about one third of Minnesota's land surface was dominated by tallgrass prairie. Of the original 7.3 million hectares of prairie, only 30,000 hectares remain today, a loss of 99.6% of the total (Samson 1994). Soils formed under perennial grasslands typically have large quantities of organic carbon as a direct result of the high root biomass and relatively rapid root turnover associated with perennial grasslands. This legacy of grasslands and carbon enrichment produced some of the finest agricultural lands in the world.

Conversion of native prairie to agricultural land and subsequent cultivation and drainage has caused significant losses of soil organic matter. Tillage and drainage both increase aeration in the soil and oxidation of organic matter. The conversion of perennial prairie grasses and forbs to annual row crops has also decreased the total annual inputs of organic matter to the soil. This combination of factors has led to a significant loss (up to 60%) of soil organic matter present in

Great Plains soils prior to cultivation (Gebhart 1994; Kucharik 2001). It has been hypothesized that all, or at least a significant portion, of this decrease in organic matter could be reversed if organic matter inputs could be increased and/or organic matter decomposition rates decreased (Conant 2001).

Perennial crops, particularly perennial grasses, may be a promising management option for carbon sequestration on agricultural lands, and particularly on marginal lands susceptible to erosion. Due to a lack of data on other systems, we consider only the establishment of perennial grasslands in this review. Much of the existing data comes from analysis of soils enrolled in the Conservation Reserve Program (CRP), established in 1985 to address soil and water quality issues related to agriculture. CRP is a voluntary program for landowners who receive payments in exchange for converting highly erodible land currently in agricultural production to perennial vegetation such as native grasses. As of February 2006, there were more than 700,000 hectares of Minnesota farmland enrolled in the CRP (USDA — Farm Service Agency 2006).

Conversion of marginal agricultural land to perennial grasses, either native or introduced, can provide carbon sequestration benefits. Estimates of sequestration rates range from 25 to 101 g C m^{-2} yr^{-1} with the highest value measured to a depth of 100 cm (Baer 2002; Gebhart 1994; Kucharik 2003; Lal 1998; Huggins 1998). A rate of carbon sequestration specific to Minnesota is 70 g C m^{-2} yr^{-1} (Huggins 1998). These increases in soil organic carbon have been observed over a five to ten year period. Similar perennial systems, such as restored prairies or grass pastures, should also be able to sequester carbon at comparable or perhaps even higher rates. Historical prairies restored with native plantings sequester carbon at a rate between 45 g C m^{-2} yr^{-1} to 75 g C m^{-2} yr^{-1} (Kucharik 2003; Potter 1999). The carbon sequestration potential of row crop conversion to pasture has been estimated at 300 (Zan et al. 2001) and 100 (Conant et al. 2001) g C m^{-2} yr^{-1}.

Increases in soil organic carbon due to perennial grass introduction is attributed to decreased physical disturbance (and hence lower aeration and organic matter decomposition rates) and increased above- and below-ground biomass inputs (Bruce 1999). Carbon accumulation rates may vary depending on inherent soil carbon status, degree of previous soil degradation, perennial species chosen for planting, previous land management, geographic location, or methodology. Grazing and haying systems, manure application rates and manure application systems, and other factors may also affect carbon sequestration rates of pastures.

Soils do not represent an infinite sink for atmospheric carbon. Increases in the rate of biomass additions to soils or decreases in the rate of organic matter decomposition will both push soils to a higher steady state condition, where the total amount of stored carbon is increased. However, those soils will eventually reach a new steady state and, assuming there are no other significant changes in rates of inputs or outputs, will maintain that steady state for some time. The length of time required before a system reaches a new steady state is unknown, but a few studies have estimated the time to steady state for perennial grassland systems. Baer et al. (2002) and Potter et al. (1999) reached estimates of 50 and 148 years, respectively, based on the assumption that the carbon accumulation rate observed proceeds linearly until the system reaches capacity.

It is unlikely that perennial grassland systems will accumulate carbon at a linear rate until steady state has been achieved. Modeling of long-term carbon accumulation in grassland soils provides support for the hypothesis that soil carbon increases at a relatively fast rate during the beginning of the carbon accumulation process, but also shows that, as time progresses, the rate of accumulation decreases until the system approaches a steady state (Parton 1988). Further research needs to be completed in order to understand how rates of carbon accumulation in grasslands change over time.

Cover Crops

Incorporation of a third crop into the biannual corn-soybean rotation provides an opportunity to sequester carbon without drastically changing land use. Corn and soybean production is a major land-use in the state of Minnesota and the Midwest in general. Because of the vast tracts of land devoted to corn-soybean production, changes in management systems that produce even modest carbon gains per hectare can produce significant increases in carbon sequestration. The use of cover crops appears to have the potential to significantly increase carbon sequestration in the corn-soybean system. Cover crops utilize solar radiation late in the fall and early in the growing season that would otherwise be wasted during periods when corn or soybeans are not growing.

Oats, wheat and rye thrive in the cool spring weather of Minnesota and are often used as over-winter cover crops. Baker and Griffis (2005) suggest winter rye and winter wheat are the best cover crops for use in Minnesota because their residue is more recalcitrant (less readily decomposed) than oat residue, and therefore more likely to contribute to organic matter. Similarly, cereal rye and annual ryegrass varieties are also considered promising cover crops in Minnesota as a means to increase soil organic carbon (Kuo 1997). Continuous cover crops, such as Kura clover, may also have the potential to significantly increase the rate of carbon sequestration in corn-soybean systems.

High-quality data on the potential of cover-cropping systems to sequester carbon are minimal. The available data suggest that cover-cropped systems have significantly higher quantities of organic carbon than non-cover-cropped systems, and offer support that these systems sequester carbon (Wander 1996). Micrometeorological studies of paired fields in Minnesota showed that the incorporation of winter rye as part of the corn-soybean rotation in Rosemount, Minnesota, demonstrated a carbon benefit ranging from 200 – 300 g C m^{-2} yr^{-1} (Baker 2005). Although only limited data are currently available, they strongly suggest that cover crops have the potential to dramatically increase the potential of the corn-soybean system to sequester carbon in Minnesota.

Peatlands and Prairie Pothole Wetlands

Wetlands, such as bogs, fens, peatlands and depressional wetlands, are unique in their ability to sequester tremendous quantities of organic carbon. The majority of wetlands in Minnesota can be categorized as either peatlands or prairie pothole wetlands. With more than 2.5 million hectares, Minnesota has more peatlands than any other state, except for Alaska. Peatlands are found in broad, flat areas with poor drainage, shallow water tables and cool climates. While biomass production is lower on these very wet soils than in more well-drained upland systems, the rates of decomposition are much much lower, with the result that the overall rates of carbon sequestration are relatively high. Unlike upland soils, peatlands do not necessarily approach a steady state for carbon inputs and outputs because the decomposition rates are so low that they often approach zero. As a result, many peatlands have been accumulating carbon at relatively slow rates since the last glaciation. Steady accumulation over thousands of years can produce very high areal values of carbon storage. Although peatlands only represent 3% of the terrestrial surface, they contain one-third of the total global soil carbon pool (Bridgham 2001).

Carbon sequestration in peatlands varies inter-annually and intra-annually depending on seasonal climate conditions such as precipitation, temperature and evapotranspiration. Extensive micrometeorological studies have demonstrated that peatlands are a sink of 60 to 80 g C m^{-2} yr^{-1} (Lafleur 2001, 2003; Moore 2002). The net ecosystem production is often much larger than is reflected by the net ecosystem exchange, as significant losses can occur outside of the growing season. These losses are large and can offset between 30% and 70% of the growing season gains (Lafleur 2003). Inter-annual variability in net ecosystem exchange is most strongly controlled by local wetness and water table fluctuations (Joiner 1999; Lafleur 2003). The carbon sequestration potential of Minnesota's vast northern peatlands resides in the natural, unmanaged character of these systems. Therefore in this literature review, peatlands are only discussed as an unmanaged terrestrial carbon sink. Where management occurs, it typically involves lowering the water table by ditching, followed by harvesting of the peat for horticultural purposes, causing a net release of carbon to the atmosphere.

The prairie pothole region is a geomorphic area of approximately 900,000 square kilometers that extends from Iowa in the southeast to Alberta in the northwest. Glaciers formed this landscape of small depressions and undulating topography about 9,000 years ago. Due to its relatively young geologic age, this landscape has had insufficient time to develop well-connected drainage networks, resulting in a landscape dotted with small depressional wetlands. Prairie pothole wetlands may be seasonally or permanently wet depending on local hydrology. Since European settlement, about 80 to 99% of wetlands in Minnesota's prairie pothole region have been drained to enhance agricultural productivity (Dickson 1993) .

Drainage of wetlands causes increased aeration of the soils and an increase in the rate of organic matter decomposition, leading to loss of organic carbon from these soils over time. Conversely, restoration of wetlands restores or mimics original hydrologic and drainage conditions and can lead to decreased rates of organic matter oxidation and the potential for increases in carbon sequestration. It is estimated that 10 metric tons of carbon per hectare has been lost from the wetlands in the Prairie Pothole region due to agricultural conversion (Euliss 2005). Because carbon storage is enhanced in wet systems, it is logical to look towards wetland restoration to sequester atmospheric carbon. Euliss et al. (2005) demonstrated that restoring local hydrology and natural vegetation in a previously drained wetland can sequester approximately 305 g C m^{-2} yr^{-1} in the upper 15cm of soil. To date, Euliss et al. (2005) are the only scientists to provide an estimate of the sequestration potentials of restored prairie pothole wetlands. More research is needed to refine the estimate the rates of carbon sequestration in prairie pothole wetlands.

Forestry

Forests have the potential to sequester large quantities of atmospheric carbon (Pacala 2001; Post 2000) through biomass production, and sometimes through contributions to soil organic matter. The carbon sequestration potential of forests depends on species composition, age, climate, and geographic location (see table 1). According to the Kyoto protocol, the carbon sequestration of existing forests in Minnesota cannot be considered a carbon credit because the forests would sequester carbon regardless of management. Only carbon sequestration associated with practices such as afforestation or agroforestry are considered carbon credits.

Table 1. Illustrates the variation in carbon sequestration related to differences in age, species, and geographic community.

Forest composition	***Stand age***	***Location***	***Sequestration Value***	***Source Data***

Maple-basswood-ash	60–80 yrs	Northern WI	334–490 g C m^{-2} yr^{-1}	(Desai 2005; Cook 2000)
Hemlock-hardwood	>300 yrs	Upper Peninsula MI	72–147 g C m^{-2} yr^{-1}	(Cook 2000)
Oak-maple-pine	50–70 yrs	Massachusetts	370 g C m^{-2} yr^{-1}	(Wofsy 1993)
Aspen-maple-oak-pine	75–120 yrs	Michigan	80–170 g C m^{-2} yr^{-1}	(Schmid 2003)
Spruce –hemlock-fir	> 100 yrs	Bangor, ME	210 g C m^{-2} yr^{-1}	(Hollinger 1999)
Ponderosa pine	9–23 yrs	Central OR	124 g C m^{-2} yr^{-1}	(Law 2003)

Afforestation

Afforestation is broadly defined as the planting of trees where trees have not existed historically or have not existed for a defined period of time. In this paper, afforestation is defined as the land-use change from cropland or pasture to forestry, or the natural succession of cropland or pasture to forest. Afforestation can sequester atmospheric carbon through carbon accumulations in the soil as well above- and below-ground biomass. Biometeorological techniques, soil sampling and biomass measurements have all been used to determine the carbon sequestration rates of afforested systems.

Biometeorological methods measure exchange of carbon between the land surface and the atmosphere for whole ecosystems, including above- and below-ground biomass, forest floor and litter debris, coarse woody material and soils. For this reason, carbon sequestration estimates derived from biometeorological techniques are often greater than estimates derived from soil sampling alone. Lee et al. measured carbon exchange of a natural successional deciduous forest system to be 130 g C m^{-2} yr^{-1} to 310 g C m^{-2} yr^{-1}. This large difference in net ecosystem exchange may be due to changes in soil temperature, ecosystem respiration, or changes in understory structure or species composition (Lee 1999). Although biometeorological techniques are quite reliable, it is difficult to separate carbon accumulation into above- and below-ground and soil components. Recent work by Zhang et al. (2006) utilizing real-time measurement of carbon dioxide isotopomers appears to provide a tool to address that issue.

Literature that reports soil carbon accumulation via soil samples often finds decreases in subsurface soil organic carbon associated with surface soil increases in young afforested systems. Degryze et al. (2004) report a carbon sequestration value of nearly 32 g C m^{-2} yr^{-1}, but this value is only significant in the upper 7cm of the soil of an afforested poplar system. Similarly, significant increases in soil organic carbon have been found in afforested oak and spruce systems, 8 g C m^{-2} yr^{-1} and 36 g C m^{-2} yr^{-1}, respectively, but only within the upper 5 cm (Vesterdal et al. 2002). Vesterdal et al. (2002) conclude that soil carbon content often decreases within the 5-to-25-cm zone following afforestation. Another literature review of soil carbon dynamics in afforested systems found consistent evidence of initial soil carbon decreases following afforestation (Paul 2002). This loss of carbon is attributed to mechanical disturbance related to site preparation that causes carbon oxidation, as well as small carbon inputs from low biomass production in a young system (Paul 2002; Turner 2000). The data provided suggest that carbon mineralization rates are larger than carbon accumulation in young afforested systems. Woody vegetation is known to be less effective at facilitating the storage of carbon in soils than other types of vegetation (Post 2000). In the short term, afforested systems are effective at sequestering above-ground carbon in biomass, but soil carbon sequestration is negligible or even negative in comparison.

A study investigating carbon storage in an afforested Loblolly pine plantation illustrates the divergence of carbon accumulation in soil from that in biomass. Over a 34 year period measurements of above- and below-ground biomass, forest litter and soil carbon storage were taken. Total ecosystem storage increased at an average of 516 g C m^{-2} yr^{-1}. Of the total ecosystem carbon storage, less than 2% was sequestered in the upper 60 cm of soil (Richter 1995). These data demonstrate that soil organic carbon accumulation in afforested systems is slow. For this reason, biomass measurements rather than soil samples are often used as a measure of carbon accumulation.

Regional biomass accumulation estimates can provide a good assessment of sequestration potential in Minnesota's afforested systems. Below is a graphical representation of carbon accumulation in biomass of different vegetation communities commonly found in Minnesota and the upper Midwest. In terms of total biomass production, Red and White Pine stands show the best carbon sequestration potential. Although pine systems reach a steady state sooner than either spruce-fir or oak-hickory systems, the total carbon accumulation is much greater. This graph also displays the length of time during which sequestration can occur before a steady state is reached. For afforested ecosystems, the window of opportunity for sequestration benefits is typically 90 – 120 years (USEPA 2005).

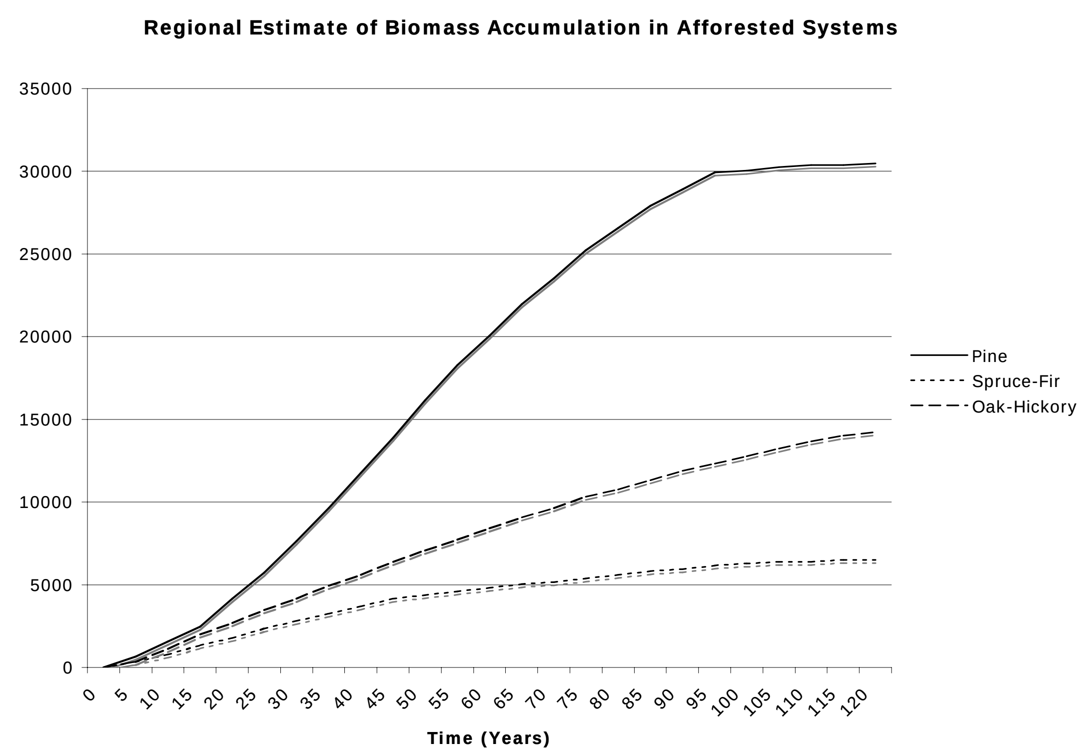

Figure 1. Values adapted from Birdsey et al., 1996. Pine and spruce-fir data from Lake State estimates. Oak-hickory data from Central State estimates. Carbon accumulation includes above-ground and below-ground biomass, including all live and standing dead trees.

Agroforestry

As defined by *The Dictionary of Forestry*, agroforestry is a land-use system that involves deliberate retention or introduction, of a mixture of trees or other woody perennials in crop and animal production systems to take advantage of economic or ecological interactions among the components. Agroforestry generally includes windbreaks, forested riparian buffers, alley cropping and short rotation woody crops. Short rotation woody crops such as hybrid poplar are becoming increasingly popular for bioenergy and pulp production. As of 1998, there were 10,000 acres of hybrid poplar planted in Minnesota, and by 2008 another 30,000 acres is likely to be planted (Josiah 1998). “Poplars” include many trees in the Salicaceae family. Hybrid poplars common in Minnesota include crosses between species such as Eastern cottonwood, Black cottonwood, Japanese poplar, European aspen, Quaking aspen, European Black poplar and Laurel-leaf poplar.

Similar to that of afforested systems, soil carbon sequestration in hybrid poplar plantations is low or negative. Literature provides evidence that soil carbon does not increase within the first 15 years of plantation establishment (Grigal 1998; Coleman 2004). Many authors actually conclude that soil organic carbon in the surface horizon initially decreases after short rotation woody crop establishment as a result of disturbance and mineralization (Grigal 1998; Hansen 1993). This effect is similar to soil carbon decreases after establishment of afforested plantations. Regardless, the magnitude of soil carbon dynamics is negligible compared to the rates of above-ground biomass accumulation.

Carbon sequestration rates for hybrid poplar biomass production are large, ranging from 240 g C m^{-2} yr^{-1} in low-productivity stands to over 1,100 g C m^{-2} yr^{-1} in high-productivity stands (Tuskan 2001; Heilman 1985). Estimates of annual biomass production for hybrid poplar stands in Minnesota are 340 g C m^{-2} and 350 g C m^{-2} (Netzer 2002; Hansen 1993). The most productive sites in Minnesota average 460 g C m^{-2} yr^{-1} with most sites reaching peak production between 7 and 10 years (Netzer 2002). There is substantial variability in the potential of soil carbon sequestration by hybrid poplars. Variability is associated with soil heterogeneity on both large and small scales, land-use history, climate, vegetative productivity, harvest interval and other management activities such as irrigation and fertilization (Grogan 2002; Heilman 1985). Soil organic carbon content prior to stand establishment also plays a role in determining sequestration potential. Research has shown that initial soil carbon content is inversely related to the rate of carbon sequestration (Grogan 2002; Garten 2002).

Conclusion

Many terrestrial land management strategies that might have the potential to sequester atmospheric carbon do not have experimental evidence to support their carbon benefit. In theory, we know that management such as cover-cropping and wetland restoration does indeed store carbon in the landscape. Unfortunately a dearth of experimental data exists to support this claim. In order to consider terrestrial carbon sequestration seriously as a mitigation strategy, further research must focus on describing the carbon dynamics of other land management systems. Such management systems to consider are grazed pasture systems, bioenergy crops, restoration of farmed wetlands, cover crops, and windbreaks. Once the scientific community has a firm understanding of carbon dynamics in a variety of land-use scenarios, best management practices for carbon sequestration can be recommended.

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