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Past and Prospective Carbon Stocks in Forests of Northern Wisconsin

A Report from the Chequamegon-Nicolet National Forest Climate Change Response Framework

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Abstract

This report assesses past and prospective carbon stocks for 4.5 million ha of forest land in northern Wisconsin, including a baseline assessment and analysis of the impacts of disturbance and management on carbon stocks. Carbon density (amount of carbon stock per unit area) averages 237 megagrams (Mg) per ha, with the National Forest lands having slightly higher carbon density than other ownership classes. Over the last decade, carbon stocks of northern Wisconsin forests have been increasing by about one teragram (Tg) per year or 0.22 megagrams per ha per year, with most of the increase in live biomass. Harvest, wind, and fire have been principal drivers of forest carbon dynamics over the last century. For all forest types in northern Wisconsin, there is potential to increase stocking on the land by allowing more of the forested area to reach older age classes or by increasing productivity. Opportunities to increase afforestation and reduce deforestation are limited, but the potential exists for utilizing biomass energy as a substitute for fossil fuels. There are several options for private landowners to participate in carbon markets or greenhouse gas registries and receive some credit for additional actions to reduce emissions or increase sequestration of carbon. The methods used here can be adapted for use by other regions or forests to assess carbon stocks and effects of management on future carbon stocks.

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A Report from the Chequamegon-Nicolet National Forest Climate Change Response Framework

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PREFACE

In recognition of the importance of forests in removing carbon dioxide (CO_2) from the atmosphere, various mechanisms have been introduced to track changes in forest carbon stocks and to provide incentives for increasing carbon stocks or sequestration rates on public and private lands. At the national scale, annual estimates of carbon stocks in forests and wood products are included in the U.S. greenhouse gas inventory submitted by the Environmental Protection Agency to the United Nations Framework Convention on Climate Change. Some states and regions have established greenhouse gas markets or registries to facilitate greenhouse gas reductions that include forestry activities on private lands, and there is an active voluntary market where payments may be made to increase carbon stocks or sequestration rates.

For public lands, a series of regulations and policies require tracking and reporting forest carbon stocks and assessing the impact of land management on carbon stocks. Executive orders, the "National Environmental Policy Act," the new "U.S. Forest Service Planning Rule," and the "U.S. Department of Agriculture Strategic Plan for 2010-2015" all include measures of forest carbon stocks and/or assessments of the main factors influencing forest carbon stocks. These regulations have prompted the Forest Service to develop a climate change performance scorecard comprised of 10 elements in order to gauge performance in a wide variety of climate change-related activities. Element 9 on the performance scorecard focuses on greenhouse gas mitigation that seeks to: (1) develop a baseline assessment of carbon stocks on National Forest lands, and (2) assess the influence of disturbance and management activities on these carbon stocks. This reflects the fact that both forest management and natural factors can influence forest carbon sequestration or emissions.

This report specifically addresses methods to achieve acceptable results for performance scorecard element 9, including the required baseline assessment and analysis of the impacts of disturbance and management on carbon stocks, using a forested region of the Eastern United States as an example. It is designed to illustrate how to apply the best available science to assess the effects of land management planning and practice on carbon in forests and wood products. Future analyses may also integrate anticipated effects on forests as a result of climate change (performance scorecard element 6) (e.g., Swanston et al. 2011) to address the potential viability of mitigation options given expected changes in climate, impacts on forest ecosystems, and management responses for adaptation.

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EXECUTIVE SUMMARY

This pilot study assesses past and prospective carbon stocks for all forest lands in northern Wisconsin and includes a baseline assessment and analysis of the impacts of disturbance and management on carbon stocks. It is designed to illustrate how to apply the best available science to assess the effects of land management planning and activities on carbon in forests and wood products. Many different influencing factors and significant uncertainties affect the choices that land managers may consider for achieving their goals for managing forests and the impacts of management on carbon stocks; therefore, this study illustrates these factors and uncertainties but does not provide a roadmap for land management decisions.

Carbon Stocks and Recent Historical Changes in Forests and Wood Products of Northern Wisconsin

- **Carbon stocks—**Carbon density (amount of carbon stock per unit area) averages 237 megagrams (Mg) per ha, with the National Forest lands having slightly higher carbon density than the other ownership classes. Total forest carbon stocks are distributed in approximate proportion to the area by ownership class. Private owners hold 63 percent of the carbon stock, followed by state and local ownership (24 percent) and National Forest (14 percent). About 60 percent of the ecosystem carbon is in the soil.
- **Changes in carbon stocks—**Over the last decade, carbon stocks of northern Wisconsin forests have been increasing by about one teragram (Tg) per year or 0.22 Mg per ha per year, with most of the increase in live biomass. Among ownership groups, the per ha increase has been largest on public forest lands. The rate of sequestration is decreasing, however, with the rate now slightly less than that of the previous decade.
- **Causes of change in carbon stocks—**Likely causes for the declining sequestration rate are continuing high rates of harvesting for wood products, which result in large areas of forest recovering from this intensive disturbance, and increasing areas of older forests where growth rates are slowing down. Since 1990, carbon in harvested wood products has increased by 0.5 Tg per year. The total net carbon sequestration in northern Wisconsin forests and wood products since 2000 was approximately 1.5 Tg per year.

Principal Factors Affecting Current and Future Forests

- **Forest area and area change—**The area of forest land increased by 3 percent in northern Wisconsin since 1990. Studies of land-cover change indicate that deforestation claimed less than 10,000 ha per year from 1990 to 2001, inferring that more than 15,000 ha per year of afforestation would be needed to result in the net forest area increase of 146,000 ha since 1990.
- **Age and condition of the region's forests—**Forests of northern Wisconsin are distributed broadly among multiple age classes, with peaks in the middle ages of the forest succession. This pattern reflects the history of land clearing for agriculture and reversion back to forest followed by periods of intensive timber harvest. The younger age classes are well represented among all ownership groups because of continuing reversions from agriculture to forest plus active forest management; young and middle-aged forests tend to be productive and healthy unless affected by a disturbance.

- **Effects of climate, air pollution, and disturbance—**Harvest, wind, and fire have been principal drivers of forest carbon dynamics over the last century in the upper Midwest. Windstorms, insects, diseases, land use change, and other disturbances also cause tree damage and mortality to varying degrees. The effects of these disturbances on forest carbon stocks are highly variable and are linked to the spatial extent and severity of a particular disturbance as well as the amount of time since disturbance. The long-term trend in productivity of northern Wisconsin forests shows the effect of recovery from intensive harvesting and fire during the early 20th century, with productivity rising as forests recovered from these historical disturbances. Nitrogen deposition has the next largest effect followed by minor influences of increasing carbon dioxide (CO_2) and climate variability, which has had a strong interannual effect but has not been very influential over the long term.

Mitigation Options for Northern Wisconsin

- **Potential carbon stocks—**Land management has long-term effects on carbon stocks, and therefore may be modified to reduce emissions or increase sequestration in forest ecosystems and harvested wood products. Forests recover lost carbon stocks in predictable patterns after reforestation, timber management, or natural disturbance. For all forest types in northern Wisconsin, there is the potential to increase stocking on the land by allowing more of the forested area to reach older age classes. On average, in northern Wisconsin ecosystem carbon could increase at an annual rate of 4.3 million Tg per year over the next 50 years in the absence of harvest, compared with the current rate of 1.5 million Tg per year, for a potential net additional increase of 2.8 million Tg per year. However, reduced harvest for wood products would cause a significant loss of carbon entering the wood products pools, and as existing forests age, their net ecosystem production declines.
- **Increasing carbon stocks in forests and wood products—**Afforestation options are limited across the northern Wisconsin landscape. Many nonforested areas are open wetlands or pine barrens which are highly valued for their ecological functions. There are multiple options for using forest management to increase carbon stocks by increasing productivity, storage, or both, but their effects are not necessarily large and may be difficult to predict because of high variability in management practices and site conditions. Harvest activities have a profound influence on regional forest carbon dynamics. The carbon retained in harvested forest products has a significant effect on the overall carbon balance of managed forests, although changes in ecosystem carbon stocks are about twice as large as changes in carbon stocks of harvested wood products.
- **Avoiding loss of forest land—**Forest loss in northern Wisconsin causes significant reductions of carbon stocks. In this region, the housing growth rate was 244 percent from 1940 to 2000, and 128 percent more growth is expected between 2000 and 2030. Reducing the rate of forest loss would avoid emissions of stored carbon. The projected baseline and the alternative scenarios for future land use predict an increase in rangelands, a major loss in pasture, a smaller loss in crops, and major gains in urban land use. Forest land use is not projected to increase. While northern Wisconsin currently has extensive forested land, it is likely to have less private forest land in the future. Although there will most likely be fairly substantial changes in land use, the differences projected by the alternative policy scenarios used in this report are relatively small.

- **Increasing use of wood for bioenergy—**There are opportunities in northern Wisconsin to utilize biomass energy as a substitute for fossil fuels. A recent analysis of available forest biomass in Wisconsin estimated that 1.5 million dry tons could be sustainably available for energy use annually at a price of $40 per dry ton. The actual amount of biomass that is available is likely less than what is potentially available because of conflicts with other owner objectives for land management. Several factors including concerns about mitigating greenhouse gases and climate change, increasing the amount of energy from domestic sources, and strengthening local and rural economies are encouraging a greater use of wood for energy in the state. Depending on the accounting framework, net forest system carbon balance may be negatively correlated with biomass harvested, illustrating the tradeoffs between increased carbon uptake by forests and utilization of woody biomass for energy.
- **Climate change and other risk factors—**Many of the stressors that currently affect the forests of northern Wisconsin may increase in importance as a result of climate change. Temperature increases and altered precipitation regimes are expected to lead to drier summer soil conditions which may make drought and associated disturbances (such as fire or pest and disease outbreaks) more prevalent. Climate change is also expected to increase the frequency and severity of extreme weather events which may lead to greater occurrence of catastrophic winds or rain events. Suitable habitat for tree species is projected to shift northward as the climate changes. Many of the area's dominant tree species are located at the southern extent of the species' range, and declines in the suitability of habitat may lead to subsequent declines in the ability of those species to persist.

Potential Pathways to Implementation

- **Participation in markets and registries—**There are several options for landowners to participate in carbon markets or greenhouse gas registries and receive some credit for additional actions to reduce emissions or increase sequestration of carbon. A universal component to any forest-based carbon project—be it afforestation, reforestation, forest management, or reduced deforestation—is dealing with several forest carbon accounting issues. The way in which these issues are defined and treated within a specific market or registry program affects the program's credibility, the project enrollment process, and the atmospheric and climate benefits of a project.
- **Public policies and regulations—**Federal and state policy guidance regarding the role that public lands may play in carbon markets is not well developed. Leading standards in the voluntary market may preclude public land participation. Within the federal government, there are several executive orders and planning regulations that require tracking of carbon stocks and assessments of future potential; however, these do not specify that a goal of land management necessarily includes increasing carbon stocks.

INTRODUCTION

Measuring and monitoring carbon and carbon dioxide (CO_2) on the land, oceans, and in the atmosphere has taken place for many decades. The global carbon budget is generally well understood, but uncertainties involving CO_2 exchanges between the land and the atmosphere still exist (Le Quéré et al. 2009). There are many variables that affect the land-atmosphere exchange at different temporal and geographic scales, such as interannual climate variability, periodic natural disturbances, a wide range of land management practices, and spatially variable emissions from burning fossil fuels.

About half of global fossil fuel emissions is absorbed by the oceans and land (carbon sinks), while the other half stays in the atmosphere contributing to the increasing concentration of CO_2 (Pan et al. 2011a), which is now about 400 parts per million or 30 percent higher than 100 years ago (National Oceanographic and Atmospheric Administration 2013). There is emerging evidence that the oceans and land may become saturated with added carbon, implying that an increasing proportion of the emitted CO_2 would stay in the atmosphere (Canadell et al. 2007).

The United States emits approximately 1.5 billion tons of CO_2 per year or about 17 percent of global emissions. About 12 percent of CO_2 emissions from burning fossil fuel is sequestered in forests and wood products each year (U.S. Environmental Protection Agency 2009); however, the effects of recent sharp increases in wildfire and insect disturbances (Man 2010, Marlon et al. 2012, Turner 2010) on forest carbon stocks are not yet fully reflected in the national-scale estimates of forest inventories.

According to some estimates, it may be possible to significantly increase the rate of carbon sequestration by forests in the United States (Lewandrowski et al. 2004, U.S. Environmental Protection Agency 2005). Key factors determining rates of sequestration are the biological potential of the land to absorb more CO_2, the economic potential as determined by the future price of CO_2 in the market, and the policies implemented at national, regional, state, and local levels.

The United States has a strong program for inventorying and monitoring emissions and sequestration in the forest sector (Heath et al. 2011), though there are some significant gaps in specific areas (Birdsey 2004). For example, the remoteness of Alaska has precluded systematic monitoring. Additionally, soil carbon is not adequately monitored except in some specific research areas even though it could be subject to significant changes given the vulnerability of this sequestered carbon to changes in climate and natural disturbance.

At smaller geographic scales, such as that of states or individual landowners, technology is available to measure, monitor, and verify carbon emissions and sequestration from individual activities or projects for the purpose of reporting to greenhouse gas registries or obtaining market credits. A variety of "carbon tools" (U.S. Forest Service 2013b) are available to support land managers and policy makers in making decisions, and methods are available to measure, monitor, and verify actions that are intended to reduce emissions or increase sequestration. Although these actions take place on the small scale of individual projects, there is a need for verification at larger scales (region, country, or global) to ensure that, collectively, the actions taken individually are having a detectable effect and that the measured effect is not reduced by reactions outside of the project boundaries (i.e., "leakage").

This report describes current carbon stocks in forests and wood products of northern Wisconsin, recent trends, and potential impacts of several greenhouse gas mitigation options that have been discussed by public and private entities in the region. Three general categories of mitigation options were analyzed for this report: (1) increase carbon stocks in forests and wood products; (2) reduce the loss of forest land; and (3) increase the use of wood for bioenergy. The report also describes opportunities and issues regarding implementation of a mitigation strategy such as engagement in greenhouse gas markets and registries. Estimates of carbon stocks and stock changes by forest ownership were derived using U.S. Forest Service Forest Inventory and Analysis (FIA) data, and models were used to assess the impacts of disturbance, climate, and land management scenarios.

This report follows the international reporting requirements established under the umbrella of the Intergovernmental Panel on Climate Change (IPCC) as implemented for the forestry sector of the U.S. greenhouse gas inventory compiled by the Environmental Protection Agency (U.S. Environmental Protection Agency 2009). The seven main forest sector carbon pools generally defined by IPCC and adapted for reporting in the United States are:

- **Live trees—**Live trees with diameter at breast height (d.b.h.) of at least 2.5 cm (1 inch), including carbon mass of coarse roots (diameter greater than a minimum size that ranges from 0.2 to 0.5 cm), stems, branches, and foliage.
- **Standing dead trees—**Standing dead trees with d.b.h. of at least 2.5 cm, including carbon mass of coarse roots, stems, and branches.
- **Understory vegetation—**Live vegetation that includes the roots, stems, branches, and foliage of seedlings (trees less than 2.5 cm d.b.h.), shrubs, and bushes.
- **Down dead wood—**Woody material that includes logging residue and other coarse dead wood on the ground that is larger than 7.5 cm in diameter, and stumps and coarse roots of stumps.
- **Forest floor—**Organic material on the floor of the forest that includes fine woody debris up to 7.5 cm in diameter, tree litter, humus, and fine roots in the organic forest floor layer above mineral soil.
- **Soil organic carbon—**Belowground carbon without coarse roots, but including fine roots and all other organic carbon not included in other pools, to a depth of 1 meter.
- **Carbon in harvested wood—**Carbon contained in products in use and in landfills. Products in use include end-use products that have not been discarded or otherwise destroyed such as residential and nonresidential construction, wooden containers, and paper products. Products in landfills include discarded wood and paper placed in landfills where most carbon is stored long-term and only a small portion of the material is assumed to degrade at a slow rate.

Carbon is transferred among these seven pools and the atmosphere (Fig. 1). The amount of carbon in each pool is commonly called a stock, and the transfers may be

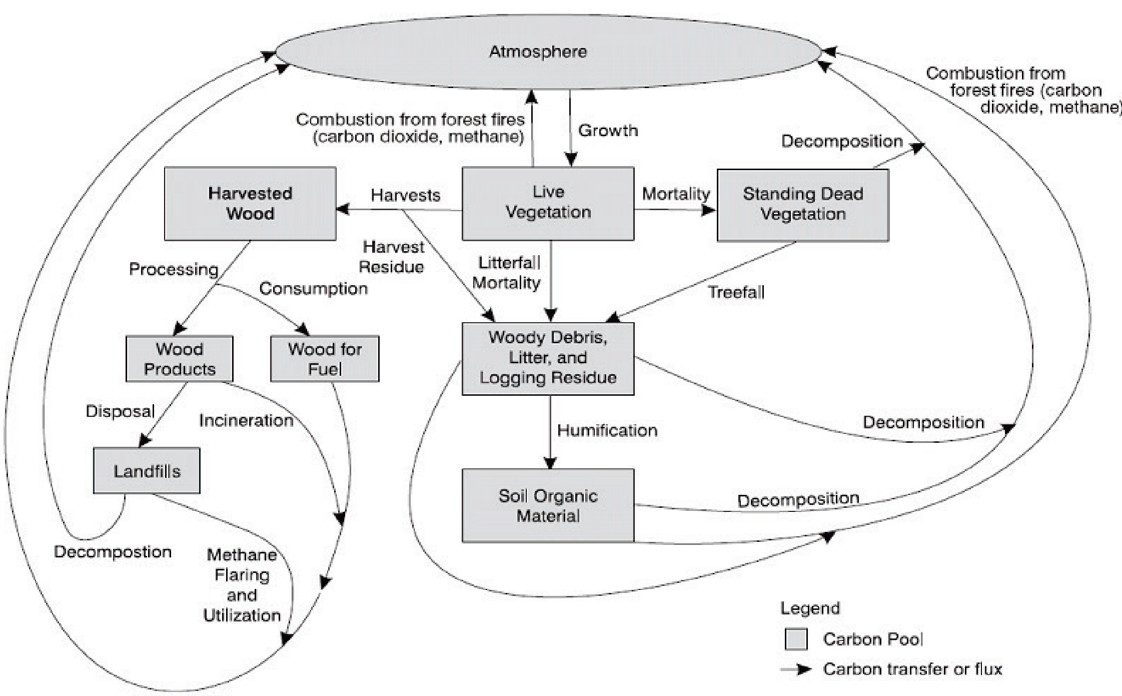


Figure 1.—Forest sector carbon pools and flows (Heath et al. 2003).

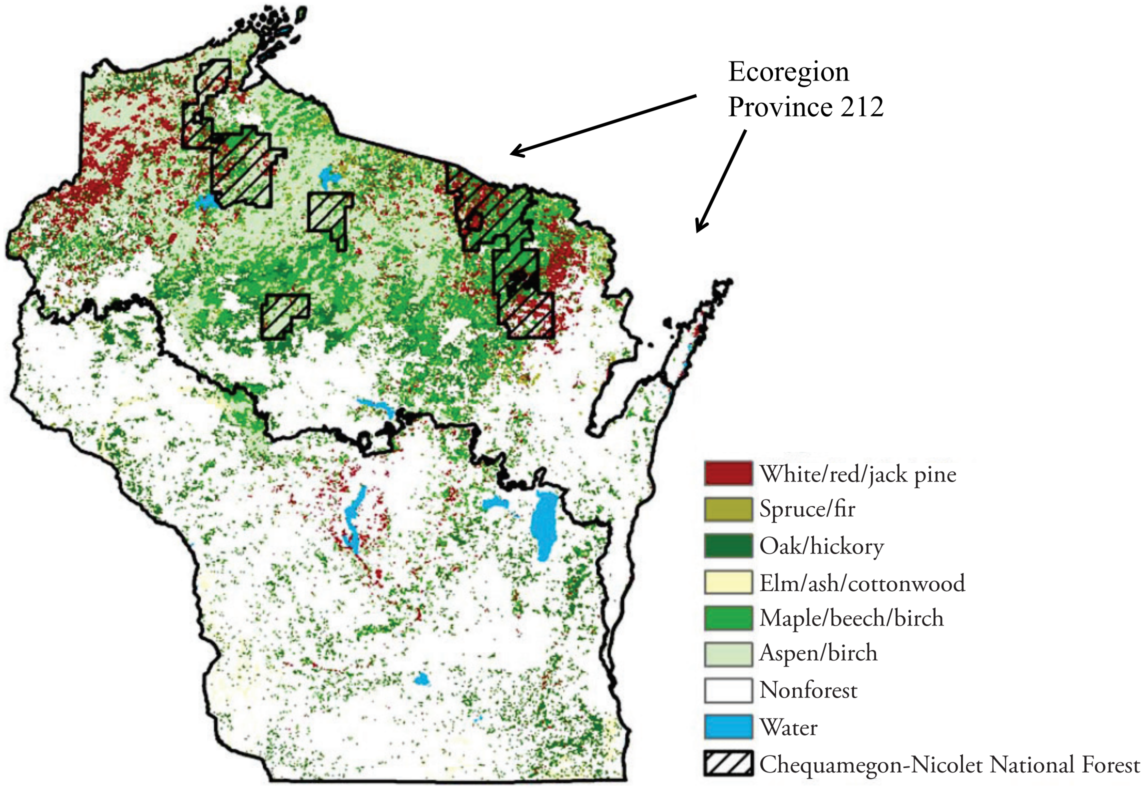


Figure 2.—Forest types of Wisconsin (Perry et al. 2008). Ecoregion Province 212 includes the northern half of the State.

called fluxes or changes in carbon stocks. These terms and some of the other common terminology used in this report are highlighted in Box 1.

The scope of analysis is the portion of Wisconsin occurring within Ecological Province 212: Laurentian Mixed Forest (Fig. 2) (McNab and Avers 1994, McNab et al. 2007). This area includes three major forest ownership groups that were used for this assessment: National Forest, other public lands, and private lands which include land owned by tribes. Northern Wisconsin is the most heavily forested region of the state, containing 4.6 million ha, or about two-thirds of the state's total forest land (Perry et al. 2008, Swanston et al. 2011). The percentage of land with forest cover increases from south to north until almost all of the land area is forest. The region's forests represent the transition from the more southerly broadleaf deciduous forest to the more northerly boreal forest. Deciduous hardwoods such as maples, ashes, and yellow birch tend to occupy high quality sites, while conifers such as pine, tamarack, and spruce occupy the less productive sites (Perry et al. 2008).

Box 1—Common forest carbon terminology and reporting units used in this report

Afforestation—The establishment of forest or forest stands on lands where the preceding vegetation or land use was not forest.

Carbon pool—A reservoir that stores carbon. Examples include forest biomass, wood products, soils, and the atmosphere.

Deforestation—Land that changes from forest to nonforest use including a significant removal of tree cover. Areas temporarily treeless from harvesting are not included if regeneration occurs.

Flux—The transfer of carbon from one carbon pool to another.

Flux tower—A tower that extends above the forest canopy, instrumented to measure the exchange of water, energy, and carbon dioxide (CO_2) between the forest and the atmosphere using a statistical technique known as eddy covariance.

Forest land—Land that is at least 10 percent stocked by forest trees of any size or formerly having such tree cover and not currently developed for nonforest uses.

Mitigation—Actions to decrease the amount of CO_2 in the atmosphere in order to reduce the effects of global warming.

Reforestation—The reestablishment of forest cover, naturally or artificially, after a previous stand or forest was removed or lost.

Sequestration—The direct removal of CO_2 from the atmosphere through biologic processes such as forest growth.

Sink—Any process, activity, or mechanism that removes CO_2 from the atmosphere.

Stock—The quantity of carbon stored in biological and physical systems, including live and dead trees and tree roots, products of harvested trees, other live vegetation, woody debris, litter, and soils.

Carbon Units—
Megagram (Mg): 1,000 kilograms (2,204.6 pounds) = 1 tonne
Teragram (Tg): 1,000,000 tonnes

PAST AND CURRENT CARBON STOCKS IN FORESTS AND WOOD PRODUCTS OF NORTHERN WISCONSIN

In this section we examine data from past periodic and recent annual inventories to develop estimates of current carbon stocks and recent trends. To the extent allowed by existing data and analyses, we identify the main causes of observed changes in carbon stocks. This information is useful both to understand the current forest situation for developing mitigation options and to establish the historical baseline for comparing with projections of changes in carbon stocks under different management and policy scenarios.

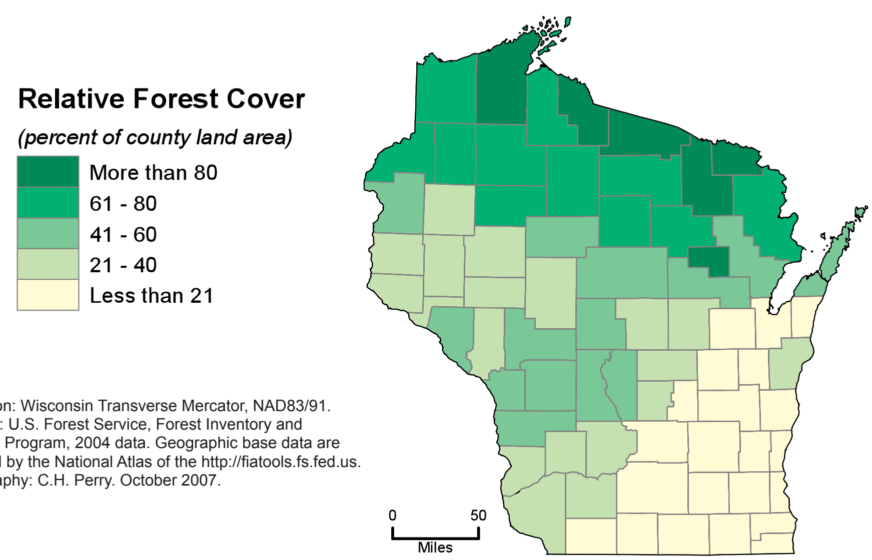
Past and Current Stocks of Forest Carbon

We used the Forest Service "Carbon Calculation Tool" (CCT) and queries of publicly available Forest Inventory and Analysis (FIA) online data sets to develop the estimates of past and current carbon stocks in this section (Smith et al. 2007). CCT is designed to estimate annual carbon stocks and changes in carbon stocks for forests at the state level for the forestry statistics of the U.S. greenhouse gas inventory (U.S. Environmental Protection Agency 2009). CCT uses FIA data from older periodic inventories, newer annual inventories, and the carbon conversion factors as described in Heath et al. (2011) to estimate annual stocks of carbon in each of the major ecosystem carbon pools since 1990. Because the standard CCT output is at the State level, we developed an historical FIA data set for Ecoregion 212 of northern Wisconsin for input to CCT so that the results pertained specifically to this region. Note that although CCT produces estimates of carbon stocks in soils at different time periods, the estimates are not sufficiently accurate to report the estimated changes in soil carbon stocks, which are generally thought to be small relative to changes in the other carbon pools.

Table 1.—Area of forest land by ownership class and year, Wisconsin Ecoregion 212

	Year		
Ownership class	1990	2000	2009
		Thousand ha	
National Forest	570.5	573.6	571.0
State and local	984.3	1,020.3	1,068.0
Private	2,815.0	2,861.8	2,877.1
All owners	4,369.8	4,455.7	4,516.0

About 64 percent of northern Wisconsin forest land is in private ownership (Table 1). Despite increasing development pressures, the area of forest land has been increasing slowly over the last decades, primarily because the rate of increase in abandoned agricultural land exceeds the losses from conversion to nonforest use. Geographically, the percentage of land classified as forest increases from south to north, with the highest forest cover occurring in the most northern counties and averaging more than 80 percent of the land area (Fig. 3).



Projection: Wisconsin Transverse Mercator, NAD83/91. Sources: U.S. Forest Service, Forest Inventory and Analysis Program, 2004 data. Geographic base data are provided by the National Atlas of the http://fiatools.fs.fed.us. Cartography: C.H. Perry. October 2007.

Figure 3.—Area of forest land by county, Wisconsin, 2004 (Perry et al. 2008).

Table 2.—Area of forest land by ownership class, year, and selected major forest types, Wisconsin Ecoregion 212

Year/Ownership class	Forest type[a]					
	WRJ	SF	OH	EAC	MBB	AB
	Thousand ha					
1996						
National Forest	55.6	87.9	11.2	34.3	222.8	155.7
State and Local	92.6	121.2	83.1	75.8	287.1	326.9
Private	147.9	313.7	216.4	276.7	1148.7	722.8
All owners	296.1	522.7	310.8	386.8	1658.6	1205.5
2007						
National Forest	52.5	95.5	28.4	19.2	213.9	146.6
State and local	105.5	139.8	118.0	47.7	255.0	322.2
Private	198.6	290.8	540.2	133.0	916.1	661.5
All owners	356.7	526.1	686.6	199.9	1385.1	1130.3

[a]White-red-jack pine (WRJ), Spruce-fir (SF), Oak-hickory (OH), Elm-ash-cottonwood (EAC), Maple-beech-birch (MBB), Aspen-birch (AB).

Table 3.—Forest carbon density for 2009 by ownership class and carbon pool, Wisconsin Ecoregion 212

Ownership class	Carbon pool				
	Biomass	Dead wood	Forest floor	Soil	Total
	MgC ha^{-1}				
National Forest	74.4	10.6	21.4	155.1	261.4
State and local	59.8	9.5	17.1	149.1	235.4
Private	65.5	9.9	16.9	140.0	232.3
All owners	65.3	9.9	17.5	144.1	236.7

Table 4.—Forest carbon stocks for 2009 by ownership class and carbon pool, Wisconsin Ecoregion 212

Ownership class	Carbon pool				
	Biomass	Dead wood	Forest floor	Soil	Total
	TgC				
National Forest	42.5	6.1	12.2	88.5	149.3
State and local	63.8	10.2	18.2	159.2	251.5
Private	188.5	28.4	48.6	402.9	668.3
All owners	294.8	44.6	79.0	650.6	1069.1

Significant changes in forest composition have occurred recently. Over the last decade, the area of oak-hickory forest has increased as the area of other hardwood forest types has declined (Table 2). These composition changes are most pronounced on private lands

Carbon density (amount of carbon stock per unit area) is high, averaging 237 megagrams (Mg) per ha, with the National Forest ownership class having a slightly higher density than the other ownership classes (Table 3). Total carbon stocks are distributed in approximate proportion to area of ownership class (Table 4). About 60 percent of the ecosystem carbon is in the soil.

Over the last decade, carbon stocks of northern Wisconsin forests have been increasing by about one Tg per year or 0.22 Mg per ha per year, a little less than the previous decade (Table 5). Most of the increase has been in live biomass. Among ownership groups, the per ha increase has been largest on public forest lands.

In summary, the forests of northern Wisconsin have been net carbon sinks for at least the last two decades, though the rate of sequestration has been declining. Public lands sequester more carbon, on average, than private lands. Likely causes for the declining rate of sequestration are increased harvesting for wood products, aging forests, and increasing natural disturbances. These driving factors are considered in more depth later in this report.

Table 5.—Average annual change in forest carbon stock by ownership class and carbon pool, 1990-1999 and 2000-2009

Years/Ownership class	Carbon pool: Biomass	Dead wood	Forest floor	Total	Average (MgC/ha)
	TgC yr⁻¹				
1990-1999					
National Forest	0.279	0.019	0.068	0.367	0.64
State and local	0.320	0.026	0.102	0.448	0.44
Private	0.644	0.012	0.045	0.701	0.25
All owners	1.244	0.057	0.215	1.516	0.34
2000-2009					
National Forest	0.192	0.008	0.080	0.279	0.49
State and Local	0.267	0.041	0.161	0.469	0.44
Private	0.370	-0.014	-0.125	0.230	0.08
All owners	0.829	0.035	0.115	0.979	0.22

Carbon in Harvested Wood Products

Change in the stock of carbon in harvested wood products is estimated as the difference between the input of carbon to wood products in use or in landfills and the emissions from these two pools. The U.S. Department of Agriculture greenhouse gas inventory (Smith and Heath 2008) estimates that harvested timber from Wisconsin forests are responsible for a net transfer of about 0.7 Tg carbon each year from live pools to wood products and landfills. The estimate of transfer to these two pools by White et al. (2005) was similar at about 0.8 Tg carbon each year.

Industrial roundwood production in Wisconsin has been relatively stable over the last two decades at about 10 million cubic meters per year (Perry et al. 2008). About two-thirds of this harvest is from northern Wisconsin—an average of 7 million cubic meters per year since 1996 (Table 6). Roundwood removals were lower overall in 2001, but the trends were different among ownership groups. Roundwood removals from National Forest lands declined significantly since 1996, while removals from both private and other public owner classes declined and then increased significantly in the most recent statistics (Table 6).

Table 6.—Average annual volume of roundwood removals, counties of Ecoregion 212 in northern Wisconsin[a]

Owner/species group	Year: 1996	2001	2006
	1000 ft³		
National Forest			
Softwood	4,827	3,568	5,872
Hardwood	14,706	12,761	5,612
Total	19,534	16,329	11,483
Other Public			
Softwood	13,848	11,851	9,996
Hardwood	45,706	41,616	46,150
Total	59,554	53,467	56,146
Private			
Softwood	37,725	35,594	39,035
Hardwood	138,583	136,417	151,735
Total	176,308	172,011	190,770
All Owners			
Softwood	56,400	51,013	54,903
Hardwood	198,995	190,794	203,497
Total	255,396	241,807	258,399

[a]Data retrieved from the Forest Inventory and Analysis timber products output database available at http://srsfia2.fs.fed.us/php/tpo_2009/tpo_rpa_int1.php. 1 ft^3 = 0.028317 m^3.

We followed the standard methodology for estimating gains and losses of carbon in harvested wood products (Skog 2008, Smith et al. 2006). The amount of harvested carbon remaining in the different carbon pools is encoded in a new harvested wood product calculator named PRESTO (U.S. Forest Service 2013d) which accepts input from the FIA timber products output database. We then used a simple spreadsheet model to estimate the carbon remaining in the products in use and landfill categories from 1950 to 2010. The period 1950 to 1990 was used to initiate variables in the model so that the decay pattern of losses from historical input to these durable wood pools was stable for the reporting period from 1990 to 2010 (Fig. 4). Results showed that since 1990, carbon in harvested wood products has been increasing by 0.5 Tg per year from timber removals in northern Wisconsin, with a reduced rate of increase in 2000 because of temporarily reduced harvest. About three-fourths of the carbon in harvested wood carbon pools comes from private lands.

Recent Changes in Carbon Stocks of Forests and Wood Products

The total net carbon sequestration in northern Wisconsin forests and wood products was 2.0 Tg per year from 1990 to 2000 and 1.5 Tg per year from 2000 to 2010 (Fig. 5). National Forest and private landowner groups exhibited reductions in carbon accumulations rates in ecosystems, while state and local ownership groups showed a small increase in the rate of carbon accumulation in forest ecosystems. There was also a significant drop in additions to the harvested wood product carbon pool for National Forests and an increase in additions to the harvested wood product carbon pool for the private ownership group.

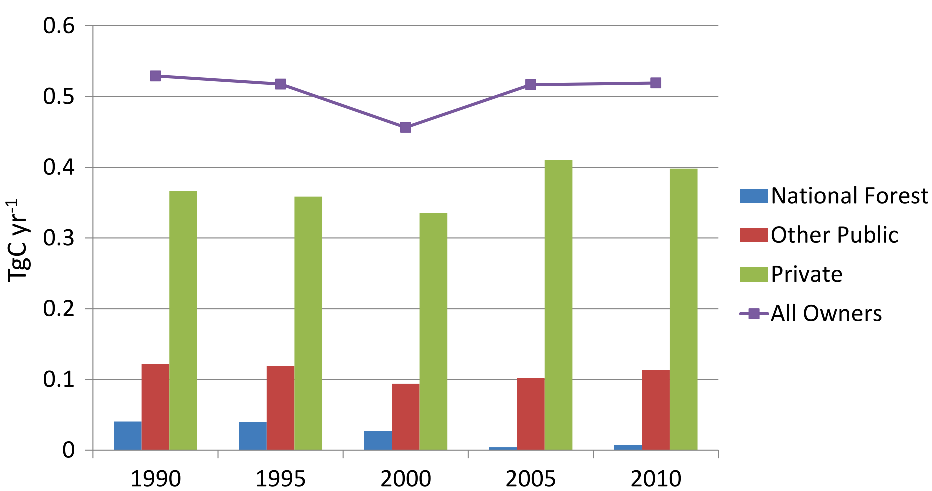


Figure 4.—Change in C stocks of harvested wood products (products in use and landfills) by ownership class, northern Wisconsin, 1990 to 2010.

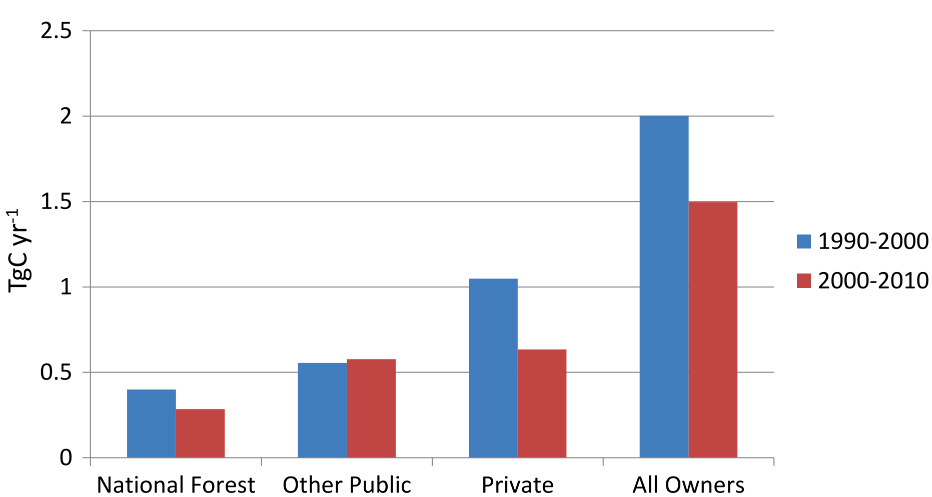


Figure 5.—Change in C stocks of forest ecosystems and harvested wood products (products in use and landfills) by ownership class, northern Wisconsin, 1990-2000 and 2000-2010.

PRINCIPAL FACTORS AFFECTING CARBON STOCKS AND FLUXES

In this section we review the main factors affecting carbon stocks and fluxes in the forests of northern Wisconsin, which will help reveal the opportunities for increasing carbon stocks in the future. We highlight stand- and landscape-level productivity estimates and their relationship to management, natural disturbance, age distribution, and current condition of the region's forests. In section 3 we use this information and that of the previous section to support analyses of management actions that could potentially be applied in the region as part of a climate mitigation strategy.

Forest Area and Area Change

The area of forest is a principal determinant of the stock of carbon and the rate of change in a landscape. Since 1990, forest land area increased by 3 percent in northern Wisconsin (Table 1). This means that losses of forest land to development and other nonforest land uses were less than additions to forest from other land uses such as cropland or pasture. About half of the counties in northern Wisconsin had either significant gains or significant losses in the total area of forest (Perry et al. 2008). Although the forest inventory does not separately report the magnitudes of gains and losses of forest area but rather the net change, studies of land cover change indicate that deforestation claimed less than 10,000 ha per year from 1990 to 2001, inferring that more than 15,000 ha per year of afforestation would be needed to result in a net forest area increase of 146,000 ha from 1990 to 2009. Even with increasing forest area, it is possible that the carbon stock declines. This is because deforestation can remove a large quantity of existing carbon stock in a very short time, whereas afforestation is a slower process of regrowth and accumulation of new carbon stocks.

Productivity of the Land

Productivity estimates can be derived from different kinds of observations, and these estimates may not be equivalent (Box 2). Northern Wisconsin has a dense network of 13 CO_2 observation sites with flux towers (see Box 1) in the region, all having similar vegetation and climate and collectively providing approximately 70 data years (Table 7). The network has discovered a range of carbon sequestration rates from very strong sinks to weak or moderate sources. Some sites switch between sinks and sources depending on year. A more detailed summary (not including net ecosystem production [NEP] rates) of the flux towers in the region can be found in Desai et al. (2008). Detailed data are readily available to the public and can be downloaded from the AmeriFlux Web site (http://public.ornl.gov/ameriflux/) or the respective project Web sites.

Table 7.—Carbon sink strength at flux tower sites in Wisconsin. Negative numbers represent ecosystems that are sources of CO_2

Site name	Status	Vegetation type	Net ecosystem production (Mg C ha^{-1})
Lost Creek	Active	Closed shrublands	0.63 to 1.02
Park Falls	Active	Mixed forest	-1.07 to -0.23
Sylvania Wilderness	Inactive	Mixed-forest (old-growth)	-1.17 to 1.47
Willow Creek	Inactive	Deciduous broadleaf forest	4.45 to 5.05
Wisconsin Clearcut Red Pine	Inactive	Open shrublands	1.67
Wisconsin Clearcut Young Hardwood	Inactive	Deciduous broadleaf forest	-0.99
Wisconsin Intermediate Hardwoods	Inactive	Deciduous broadleaf forest	1.11
Wisconsin Intermediate Red Pine	Inactive	Evergreen needleleaf forest	8.67
Wisconsin Mature Red Pine	Inactive	Evergreen needleleaf forest	8.53 to 9.55
Wisconsin Mixed Young Jack Pine	Inactive	Evergreen needleleaf forest	5.73
Wisconsin Pine Barrens	Inactive	Open shrublands	2.72
Wisconsin Young Jack Pine	Inactive	Evergreen needleleaf forest	2.72 to 3.24
Wisconsin Young Red Pine	Inactive	Evergreen needleleaf forest	4.74

Box 2—Forest processes affected by natural disturbances and management practices

Timber harvesting, fire, weather events, and many other disturbances affect a variety of processes that determine the net carbon balance of an ecosystem and how that balance changes over time. Some types of ecosystem models simulate the responses of these processes and predict how different ecosystem carbon pools may change after disturbances.

- **Gross Primary Production (GPP)**—ecosystem-level gain of CO_2 from photosynthesis, a process by which green plants utilize the energy of sunlight to manufacture carbohydrates from carbon dioxide and water in the presence of chlorophyll.
- **Autotrophic Respiration (R_a)**—Oxidation of specific organic molecules by photosynthetic plants with a subsequent release of CO_2.
- **Net Primary Production (NPP)**—GPP minus R_a.
- **Heterotrophic Respiration (R_h)**—Release of CO_2 by nonphotosynthetic organisms that obtain nourishment from the ingestion and breakdown of organic matter.
- **Net Ecosystem Production (NEP)**—NPP minus R_h.
- **Net Ecosystem Carbon Balance (NECB)—**NEP minus carbon losses to disturbances or other transfers from the ecosystem (e.g., ecosystem carbon removed by fire or forest management).
- **Net Biome Production (NBP)**—NECB integrated over time and space.

Using data from a very tall tower (much taller than the flux towers reported in Table 7) representing a large heterogeneous landscape, Davis et al. (2003) found that the ecosystems in the region were, on average, carbon neutral. The tall tower represents a landscape that includes aspen, northern hardwood, and coniferous stands, and about 30 percent of the area is shrub or forested wetland. The average stand age is 51 for uplands and 69 for wetlands (Davis et al. 2003).

A tower in the Sylvania Wilderness Area documented a small carbon sink (Desai et al. 2005), consistent with most other older forest sites in the Fluxnet network which have shown small to moderate carbon sinks (Griffis et al. 2003, Hollinger et al. 1994, Knohl et al. 2003). However, the carbon sequestration value (net ecosystem exchange, NEE) for Sylvania was only 11 percent of that for Willow Creek; the mature forest at Willow Creek was a much stronger carbon sink.

Additional towers were located in several forest types on the Washburn District of the Chequamegon-Nicolet National Forest (CNNF) including young red pine, mature red pine, young hardwood clearcut, mature hardwood, and pine barrens. Age, not species composition, appeared to be the more important factor in this study. Mature red pine and mature hardwoods had nearly equal values (6.48 and 6.55 Mg C per ha per year, respectively) although this study only took observations during the growing season, making them significantly higher than if the observations were made year round (Noormets et al. 2007).

Land use history, species composition, age, and soil characteristics are possible reasons for the differences in the productivity estimates for these sites (Cook et al. 2004). Broadleaf trees typically have higher maximum rates of CO_2 uptake than conifers, but because conifers are usually evergreen, their uptake rates over the whole year can be similar (Malmsheimer et al. 2008).

Bradford and Kastendick (2010) used a chronosequence approach to study carbon storage in pine and aspen-birch systems in nearby Minnesota. They found that total carbon storage, along with structural complexity, increased with stand age. However, in these previously harvested systems (which were depleted of course woody debris, and thus had lower rates of decomposition), the young stands had the highest rates of carbon sequestration. This highlights some of the possible tradeoffs managers will face in deciding whether to favor younger or older forests. Interestingly, this study also found that older aspen stands continued to accumulate carbon well beyond the current recommended management rotation of 30 to 60 years.

Using plot-based techniques, aboveground net primary production (NPP) for mixed hardwood stands in the region has been estimated at 3.75 Mg carbon per ha per year using data collected from 1998 to 2000 (Burrows et al. 2003) and 3.30 Mg carbon per ha per year using data collected from 1993 to 1994 (Fassnacht and Gower 1997). Wang et al. (2009) used a model approach and estimated ecosystem NPP to be 7.30 Mg carbon per ha per year for a mixed hardwood forest. Combining flux towers and remotely sensed data to produce a landscape level estimate of NEP, Cook et al. (2009) found a sequestration rate of 3.84 Mg carbon per ha per year. Peckham et al. (2012) estimated an average net biome production (NBP) of 2.3 Mg carbon per ha per year using the model Biome-BGC, which showed a range of 1.6 to 3.0 across the landscape.

Land Management

Effects of Forest Management on Carbon Stocks and Fluxes

Forest management strategies can be designed to manipulate carbon stocks and rate of carbon uptake by forest systems. The impact of a selected management strategy will depend on the type of the management practices (e.g., thinning, prescribed burning), how these practices transfer carbon between the different carbon pools, the time period between disturbances or management practices, and the area of forests under management. Several basic ecosystem processes (Box 2) are affected by management practices, and together these processes determine the overall carbon balance (Harmon 2001, Harmon and Marks 2002, Pregitzer and Euskirchen 2004).

Time since disturbance, whether natural or human-caused, largely determines whether a forest system is a net source or sink of carbon. In general, forest stands recovering from disturbance are sources of carbon until uptake from growth becomes greater than losses due to respiration, usually within 10 years (Amiro et al. 2006).

When forests are clearcut, carbon is removed for wood products, and residual carbon stocks, such as woody debris and litter, decompose. It typically takes several decades for the ecosystem carbon stocks to recover to the preharvest level. The time it takes to recover is highly variable, depending on site productivity, regeneration success, species, climate, and other factors, but the forest will eventually recover the emitted carbon unless the soil, climate, or other environmental conditions have changed.

The conversion of mature forests into young, intensively managed stands may change a landscape from a sink to a source because of increased emissions from harvesting and because reduced leaf area of the regenerating stand leads to lower photosynthesis and NEP (Janisch and Harmon 2002, Schulze et al. 2000). However, carbon losses after timber harvest can be reduced by efficient utilization of harvested wood and maintaining a certain level of leaf area of the residual stand (Chen et al. 2004). Generally, reducing the harvest of live trees from complete removal to 20 percent removal could increase carbon stocks by 20 to 50 percent, depending on the harvest interval (Ryan et al. 2010).

Smith et al. (2006) developed forest ecosystem carbon yield tables using Forest Inventory and Analysis (FIA) data, conversion factors, and forest growth-yield models to represent stand-level merchantable volume and carbon pools as a function of stand age for 51 forest types within 10 regions of the United States. Separate tables were developed for afforestation and reforestation. Calculations of carbon sequestered in harvested wood products were also included. Estimates in Smith et al. (2006) represent average values for forest types within large regions containing substantial site variability; therefore, the uncertainty of the estimates if applied to a specific forest stand may be high relative to other techniques that use site- or project-specific data. The estimates showing the average response of forest carbon pools to management and disturbance may be used for strategic analysis and in some cases, estimating and reporting actual changes in carbon stocks from forestry activities (e.g., Birdsey 2006).

NEP was calculated for three different forest types typical of northern Wisconsin using the estimates from Smith et al. (2006). The rate of carbon sequestration after clearcut harvest is zero or negative for about a decade due to decomposition of residual carbon primarily from the forest floor and woody debris pools (Fig. 6a). It then increased to a maximum rate at 20 to 35 years of age, followed by a long period of slow reduction in rate of uptake. The results are slightly different for afforestation, here defined as reversion of cropland back to forest (Fig. 6b). In this case there is no loss of stored carbon because the forest floor and woody debris pools are absent at age zero, and the maximum rate of NEP is a little higher in the early decades because of buildup of soil carbon after depletion from cultivation.

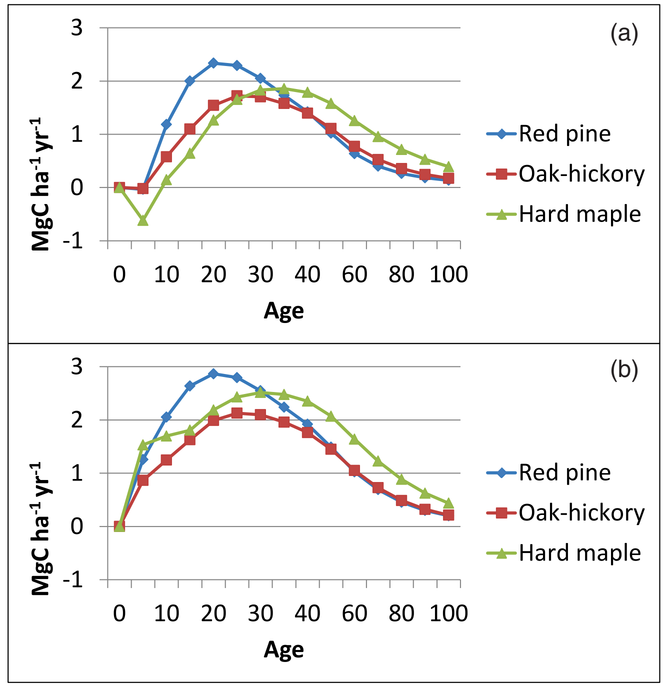


Figure 6.—Net ecosystem production of selected forest types (a) after clearcut harvest, and (b) after afforestation. Estimates are from Carbon OnLine Estimator (COLE), data retrieved April 12, 2010.

Carbon in Harvested Wood Products

Carbon stocks that are transferred by harvest from ecosystem carbon pools to wood products retain some portion of carbon removed from the forest over the long term (Skog 2008, Smith et al. 2006). It is important to keep track of the carbon sequestered in harvested wood products until it returns to the atmosphere. How long the carbon is retained is determined by the kind of products produced (e.g., lumber, pulpwood) and how these products are disposed of (e.g., landfilled, combusted). Figure 7 shows a typical retention pattern for carbon in harvested hardwood of the Lake States. If all of the harvested hardwood were used for sawn timber rather than pulpwood, 37 percent of the carbon removed from the forest would still be in use or in a landfill after 65 years.

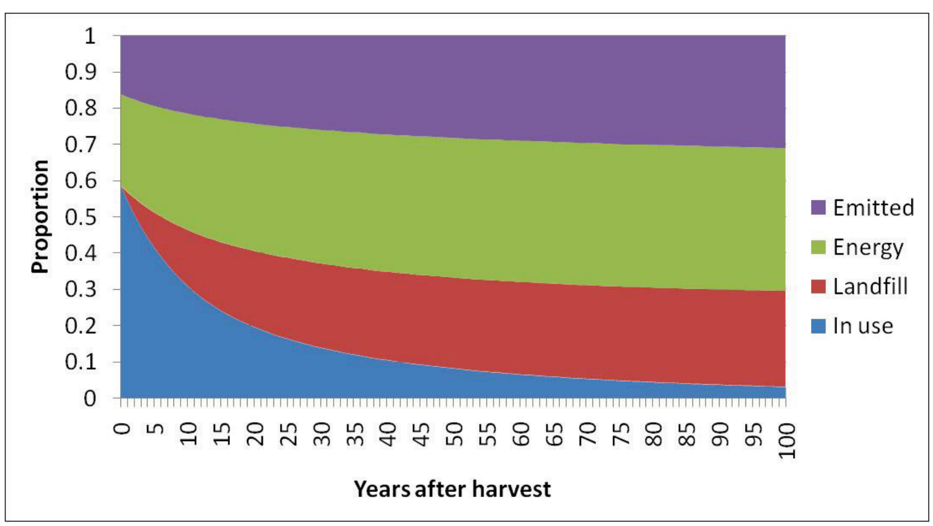
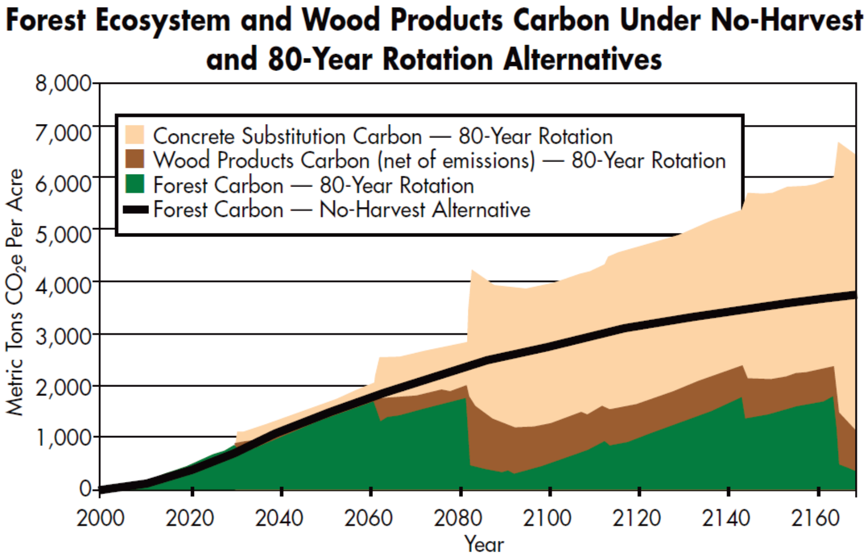


Figure 7.—Disposition of carbon in harvested hardwood over 100 years in the Lake States. **In use** refers to wood products still in use. **Landfill** refers to wood that has been disposed of, yet the carbon is still sequestered in a landfill. **Energy** refers to the amount of harvested wood burned for energy. The remainder is **Emitted**. From Smith et al. (2006).



Adapted from Wilson 2006, data from Perez-Garcia et al. 2005

Figure 8.—Comparison of changes in carbon stocks for no harvest and multiple rotation scenarios. From Ingerson (2007).

A common question is whether harvesting and regeneration on a repeated rotation sequesters more carbon than leaving a forest to grow without harvest (assuming no natural disturbance). The answer often depends on the time horizon. For a short period of time of several decades or so (actual timing depends on growth rates and other factors), leaving a forest intact will sequester more carbon than harvesting and regenerating. Over a longer time period, repeated harvesting and regeneration can provide more total carbon storage in the ecosystem plus wood products if substitution of wood for other materials is part of the accounting system (Fig. 8). This conclusion is based on data showing that there may be substantial energy savings if wood is used instead of other products that consume more energy in production.

Landscape-scale Considerations

In a landscape that contains forests with different disturbance histories and age classes, some stands are likely to be carbon sources (releasing carbon to the atmosphere), others are likely to be carbon sinks (removing carbon from the atmosphere), and some may be close to a balanced state (Harmon 2001, Jarvis et al. 2005). Adding together all of the individual stand-level estimates determines overall landscape-level carbon stocks and fluxes (Fig. 9). A single stand shows the typical dynamics of recovering carbon stocks following a disturbance, but when carbon stocks of multiple stands are averaged together, the line flattens as the aggregate values represent the entire landscape.

Whether a landscape is a carbon sink or source reflects its site quality, species composition (forest type), management history, and time since last disturbance or age-class structure. The average carbon stock of a large number of stands is determined by the interval and severity of disturbances over the landscape. With more frequent and severe disturbances, the average carbon stock (including stock in harvested wood products) becomes lower. Practices designed to enhance carbon sequestration at the landscape scale must replace ecosystems having lower carbon densities with ones having higher densities. Examples of these practices include: reducing the severity of disturbances, increasing the time interval between disturbances, emphasizing long-lived forest products, or reducing decomposability of dead material.

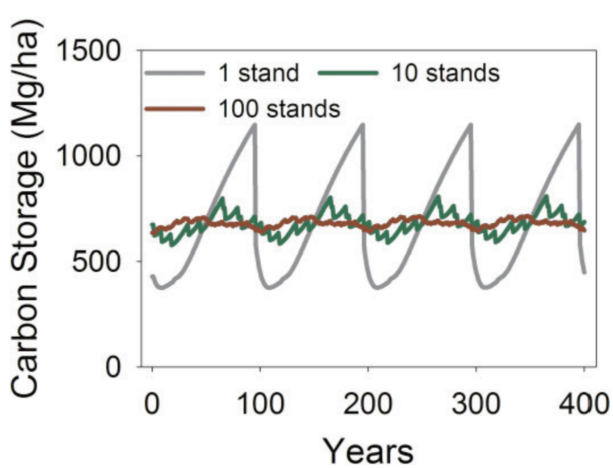


Figure 9.—Carbon storage over time of a single stand and averaged over multiple stands (McKinley et al. 2011).

Age and Condition of the Region's Forests

Young, rapidly growing forests, once established, have higher rates of carbon sequestration but lower levels of stored carbon compared with older forests. In contrast, older forests have higher levels of stored carbon, but lower rates of net sequestration due to greater mortality and respiration (Harmon 2001, Malmsheimer et al. 2008). Late successional and old growth forests may capture less or perhaps even no new carbon from the atmosphere, but they can store large masses of carbon in biomass and soils for long time periods (Harmon 2001). At any time, the balance between production, decomposition, and horizontal or vertical transfers into and out of a forest stand determines whether the forest is a net source or a net sink of carbon; however, over the long term, the average amount of carbon stored on a landscape is a more stable indicator of the impacts of management.

The forests of northern Wisconsin have a distribution of age classes that peaks in the middle ages of a forest life cycle, a pattern typical of northern U.S. forests (Fig. 10) (Pan et al. 2011b). Generally, this pattern reflects the history of land clearing for agriculture and reversion back to forest and periods of intensive timber harvest during the last century. Because of continuing reversions plus active industrial forest management, the younger age classes are well represented among all ownership groups. The oldest forests sampled by FIA in the region are about 200 years old. There is a slightly higher proportion of older-aged forests on Federal lands. Young and middle-aged forests tend to be productive and healthy unless affected by a disturbance.

Distributions of age classes by forest type show distinctively different patterns (Fig. 11). The white-red-jack pine and aspen-birch forest type groups tend to be younger on average, reflecting plantation and early-successional management, respectively, for industrial wood products. Spruce-fir, oak-hickory, and maple-beech-birch all show the typical northeastern pattern of higher proportions of middle-aged forests.

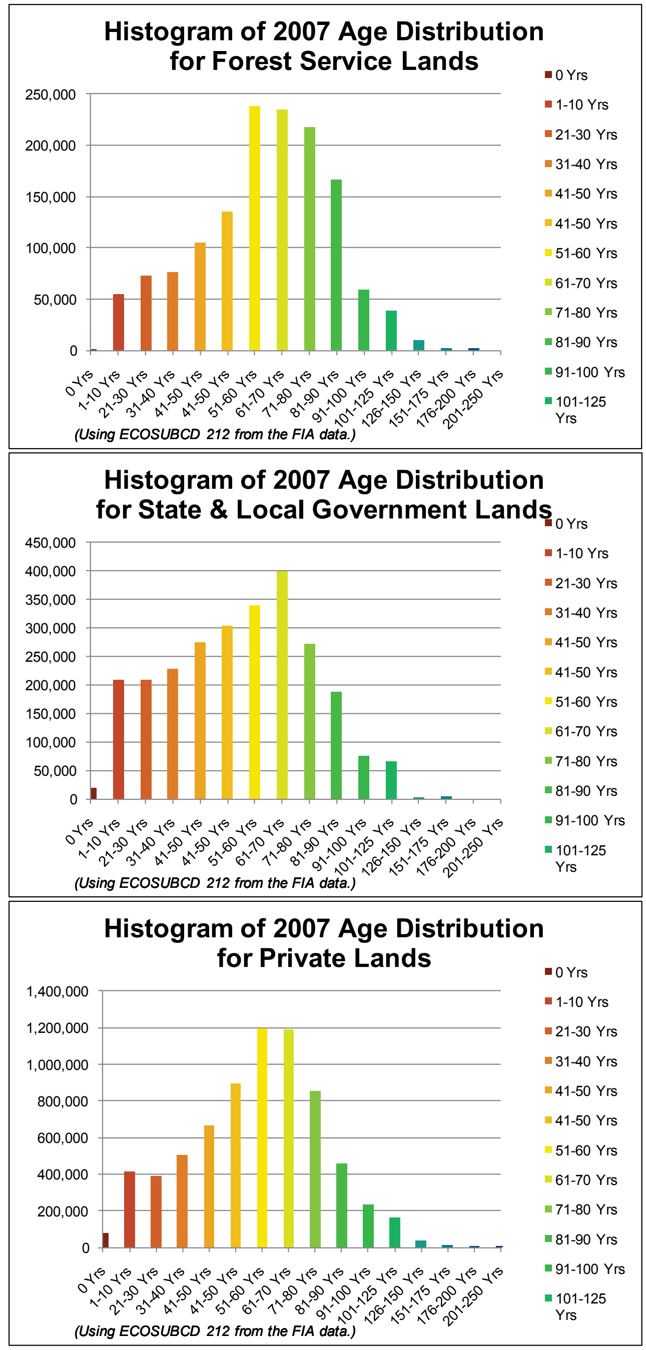


Figure 10.—Area of forest in 2007 by age class and ownership class, northern Wisconsin.

The age-class distribution over a landscape, which reflects the legacy of past harvest, natural disturbance, and abandonment of agriculture, is a useful indicator of potential for additional carbon storage. If the landscape is dominated by young forests, there is significant potential to increase carbon stocks, whereas an area with mostly old forests will not likely increase carbon stocks significantly in the future.

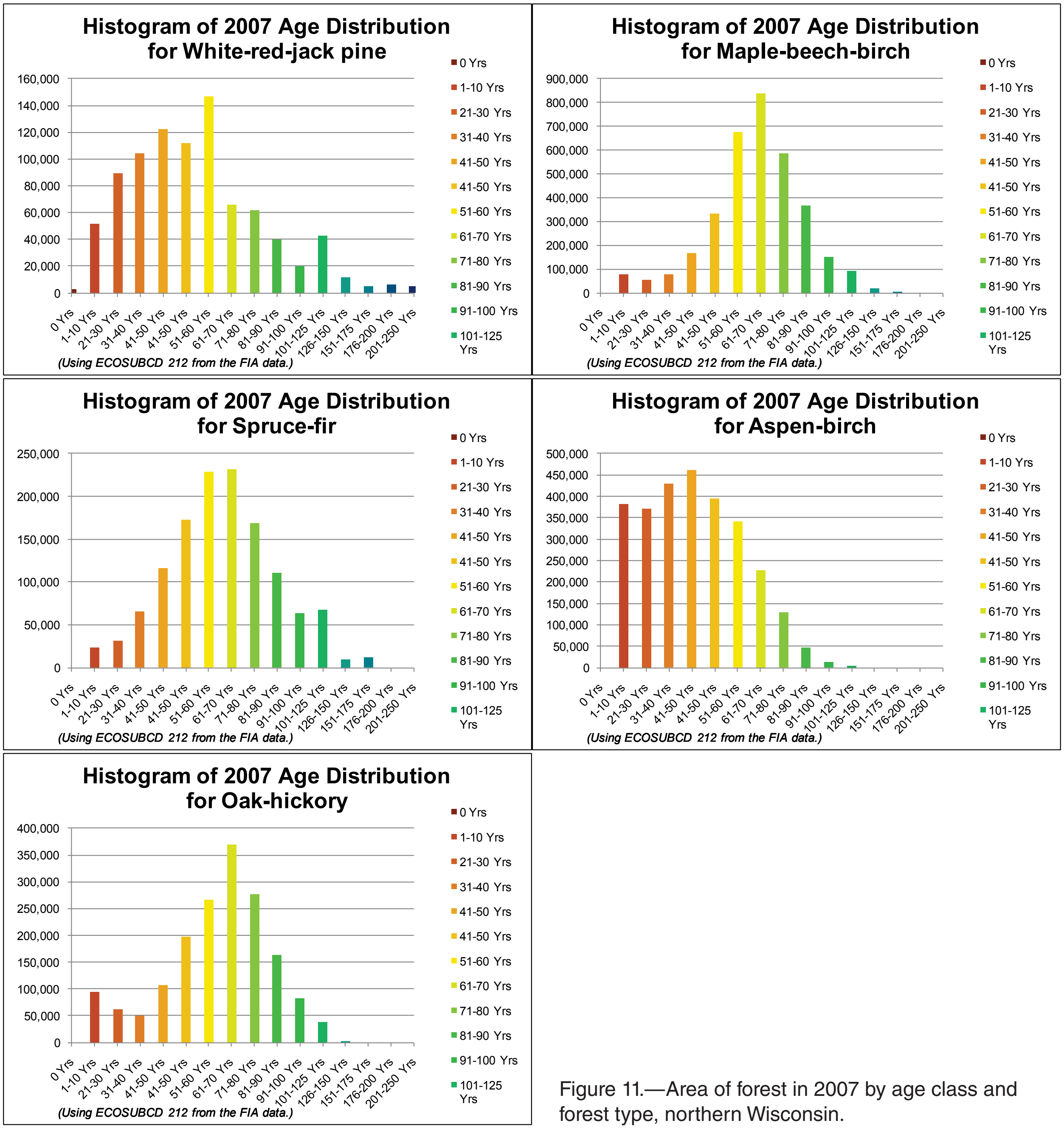


Figure 11.—Area of forest in 2007 by age class and forest type, northern Wisconsin.

Effects of Climate, Air Pollution, and Natural Disturbance

Harvest and fire have been principal drivers of forest carbon dynamics over the last century in the upper Midwest (Gough et al. 2007). Windstorms, insects, diseases, and other disturbances such as land use change also strongly affect the natural systems of northern Wisconsin and cause tree damage and mortality to varying degrees (Mladenoff et al. 2008). Wind and fire have historically been the most destructive natural disturbances. Although fires during settlement times, often as a result of land clearing, had substantial effects on the landscape, wind appears to have had significantly greater effects than fire on Wisconsin's forests over long periods of time (Mladenoff et al. 2008, Schulte and Mladenoff 2005). The effects that these disturbances have on forest carbon budgets are highly variable and linked to the type of disturbance, the spatial extent and severity of a particular disturbance, and the amount of time since disturbance (Gower 2003). Collectively, past disturbances have long-lasting effects on the ability of forests to sequester carbon (Gough et al. 2008).

Atmospheric pollutants also have wide-ranging effects on forest carbon. Ozone is a well-known damaging air pollutant that has adverse effects on forest productivity (Gower 2003). Ozone damage is a threat in areas of higher concentration, though northern Wisconsin forests are relatively free of damaging exposure (Perry et al. 2008). Nitrogen deposition and CO_2 fertilization have complex effects on forest productivity and may increase productivity in some instances, while causing negative (for nitrogen) or neutral (for CO_2) impacts on forest carbon in others (Gower 2003).

We used the Integrated Terrestrial Ecosystem Carbon Cycle Model (InTEC) to quantify the historical effects of disturbance factors (harvesting, fire, insect infestation) and nondisturbance factors (CO_2 concentration, N deposition, climate variability) on productivity and carbon stocks of the continental United States, including northern Wisconsin (Chen et al. 2000a, 2000b; Zhang et al. 2012). The InTEC model is process-based, closely calibrated to FIA and other observational data, and validated at the regional scale (Box 3) (Zhang et al. 2012). For northern Wisconsin we used a simple downscaling approach by extracting results based on the geographic boundary of Ecoregion 212 (Fig. 12).

The long-term trend for forest productivity in northern Wisconsin shows the effect of forest recovery from intensive harvesting and fire of the early 20th century, with productivity rising as forests recovered from these disturbances (Fig. 13). The model results suggest that vegetation recovered first, followed by an increase in soil carbon that may now be approaching the rate of increase in aboveground carbon. Overlaid on these long-term trends is the strong effect of interannual climate variability, which results in substantial year-to-year changes in productivity across much of the historical reconstruction (Fig. 13). The effect of climate variability is more pronounced on vegetation than soil,

Box 3—Description of the Integrated Terrestrial Carbon Cycle Model (InTEC), from Zhang et al. (2012)

The carbon balance of a forest ecosystem is the sum of changes in vegetation (living biomass) and soil carbon pools, which in turn result from net primary production (NPP) over a specified period of time (Chen et al. 2000a). Since NPP changes with climate, atmospheric composition, soil conditions, and disturbances, the carbon balance of a forest region is a function of these external forcing factors (Chen et al. 2000b). The model includes five core processes:

1. Simulation of gross primary production (GPP) using a two-leaf canopy photosynthesis model based on Farquhar's leaf-level biochemical model (Chen et al. 2000a), and spatial distributions of GPP as well as NPP in a recent reference year (NPP_{ref}) are modeled using spatial datasets of leaf area index (LAI), clumping index, land cover, soil texture, and hourly meteorology.
2. Based on the NPP distribution in NPP_{ref}, annual historical NPP is reconstructed retrospectively based on past climate data.
3. Normalized NPP-age relationships derived from the FIA data are used to determine patterns of forest regrowth after disturbances (He et al. 2012).
4. A three-dimensional distributed hydrological model is used to simulate soil moisture and temperature (Ju and Chen 2005).
5. A modified CENTURY model (Parton et al. 1987) and the net N mineralization model of Townsend et al. (1996) are employed to simulate soil carbon and N cycles.

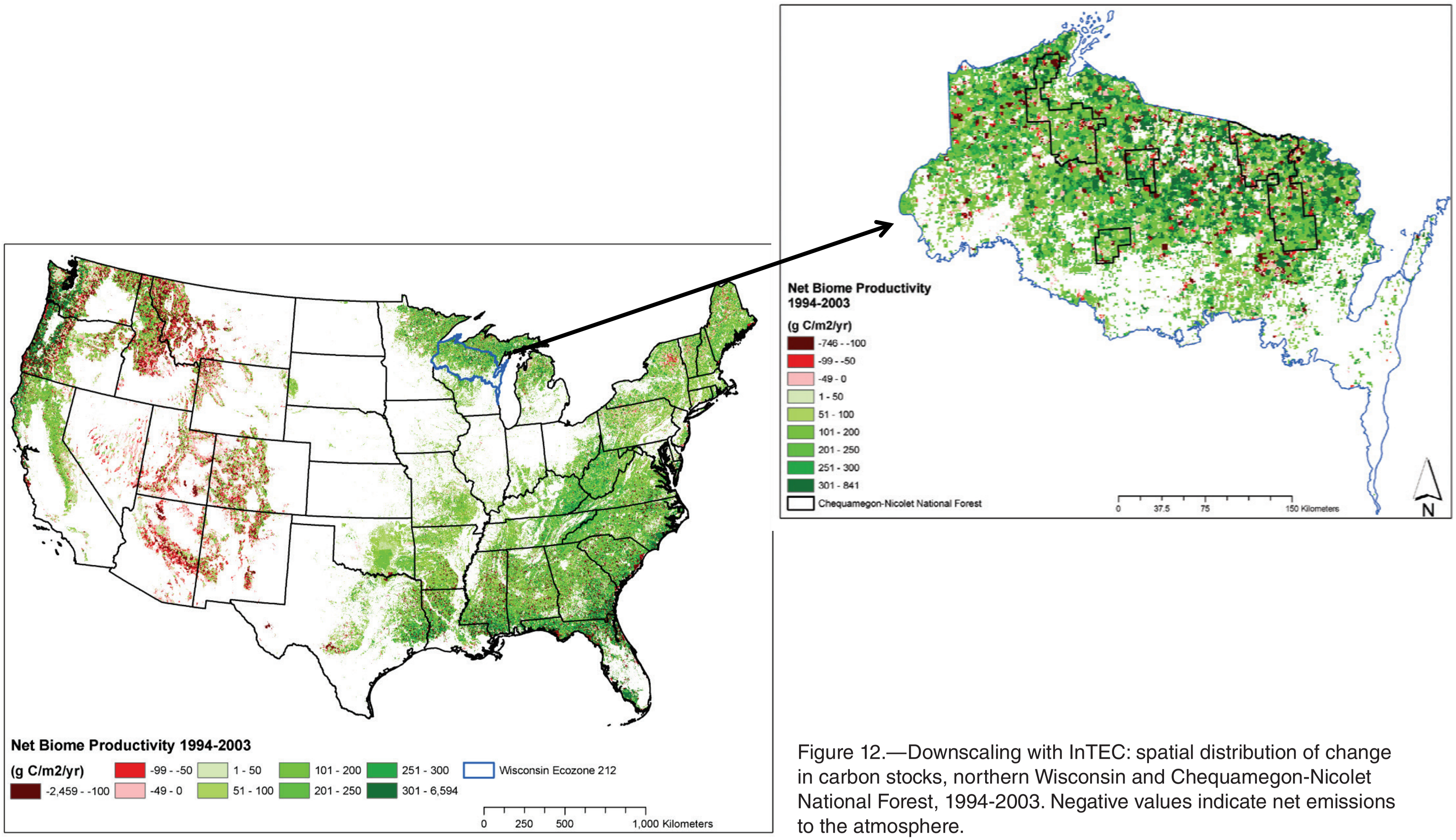


Figure 12.—Downscaling with InTEC: spatial distribution of change in carbon stocks, northern Wisconsin and Chequamegon-Nicolet National Forest, 1994-2003. Negative values indicate net emissions to the atmosphere.

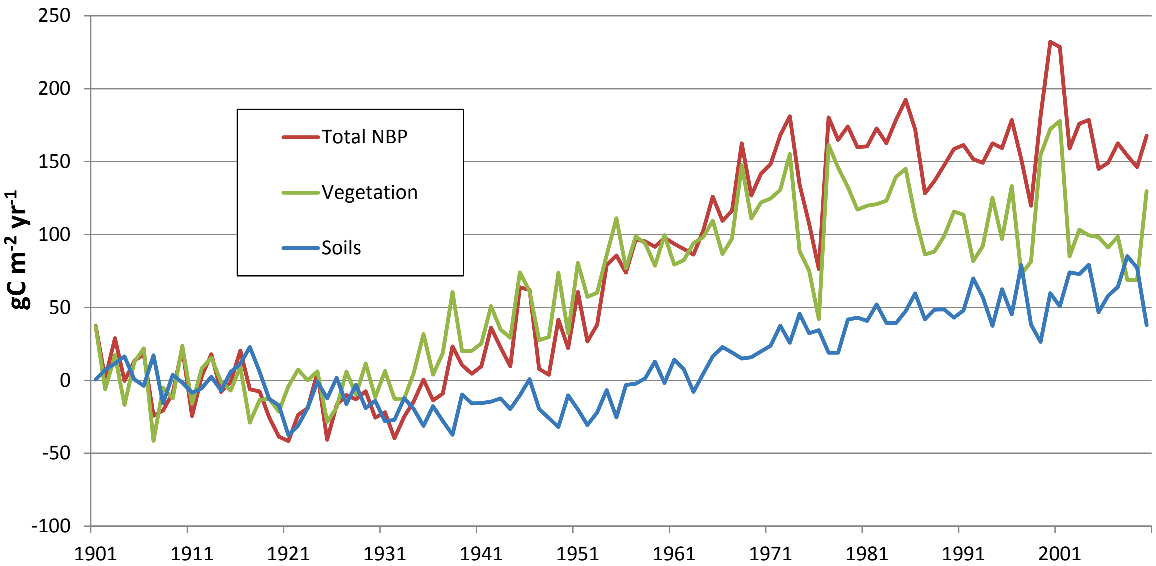


Figure 13.—Net biome productivity (NBP) of vegetation and soils in forests of northern Wisconsin, 1901-2010 (Zhang et al. 2012). Negative values indicate net emissions to the atmosphere. Land use change is not accounted for in these estimates.

though there is a noticeable lagged response. Some of the years with high reductions of productivity appear to correspond with El Nino climate events which are known to alter precipitation and will likely result in higher than normal rainfall in the Lake States (Holmgren et al. 2001).

Among the main factors affecting cumulative productivity, the regrowth and disturbances cycle has by far the largest effect, accounting for about two-thirds of the total (Fig. 14). Nitrogen deposition has the next largest effect, followed by the minor influences of increasing CO_2 and climate variability which causes a strong interannual effect that has not been very influential over the long term.

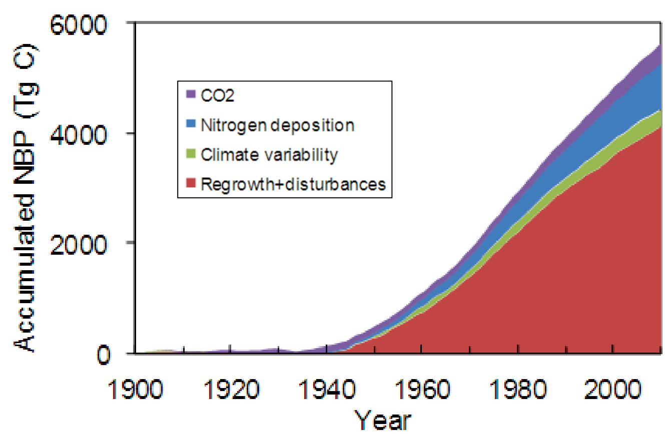


Figure 14.—Cumulative net biome production (NBP) for northern United States attributed to principle driving factors (Zhang et al. 2012).

MITIGATION OPTIONS FOR NORTHERN WISCONSIN

Northern U.S. forests are highly diverse ecosystems with different patterns of land use history. Forest management has adapted locally to this diversity and to various federal and state regulations. Because carbon is not often the main goal of land ownership, mitigation is generally considered in the context of multiple goals and objectives. Broad categories of forestry activities that can contribute to increasing carbon stocks or reducing emissions include:

- increasing carbon stocks in forests and wood products including reducing loss from disturbances
- avoiding loss and fragmentation of forest land
- increasing the use of wood for bioenergy

These activities can be consistent with many common landowner objectives such as timber production, provision of wildlife habitat, and watershed protection. At the same time, there may also be tradeoffs. For example, greater amounts of carbon can be stored in trees and long-lived wood products when forests are allowed to mature, but the transition to older forests may reduce early successional habitat for some common wildlife species.

McKinley et al. (2011) summarized current knowledge about forests and carbon storage in the United States and described forest management strategies that can increase forest carbon, prevent its loss, and/or reduce fossil fuel consumption. Each strategy has tradeoffs, risks, and uncertainties which are vital considerations for any effort to promote forest carbon storage, especially with the uncertainty of forest growth and disturbance under future climate. The effectiveness of each strategy depends on many factors including time horizon of analysis, geographic location, forest type, and specific practices applied. A literature review of many specific studies in the United States is also available (Hines et al. 2010). See Box 4 for a summary of mitigation activities, examples of tradeoffs, and a description of some issues for managers to consider.

Potential Carbon Stocks

Historical data for northern Wisconsin show that significantly higher biomass existed in prelogging forests compared to today, which illustrates that it is theoretically possible to restore large areas of forest to historically higher levels of carbon stock (Rhemtulla et al. 2009). For all forest types in northern Wisconsin, there is potential to increase stocking by allowing more of the forest area to reach older age classes. However, the reduction in harvesting for wood products would cause a significant decline of carbon entering the wood products pools, and as existing forests age, their net ecosystem production declines as shown in Figure 6. Nonetheless, with annual change in carbon stocks (excluding soil C) averaging 0.22 MgC/ha (Table 5), there should be identifiable opportunities to increase carbon sequestration by following some of the management practices described in the literature.

Rhemtulla et al. (2009) estimated that aboveground carbon density in Wisconsin's forests could be doubled if existing forests were allowed to grow to old age and all suitable agricultural land were converted to forest and allowed to fully regrow. Most of the existing forest recovery would take place in northern Wisconsin, but only about a third of the potential reversion of agricultural land would occur there (Fig. 15). These estimates assume that the effects of CO_2

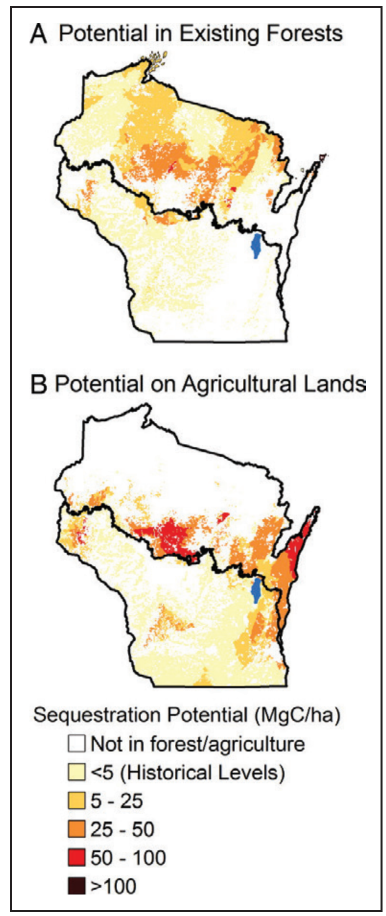


Figure 15.—Potential increases in aboveground carbon density if existing forests were allowed to grow to old age and all suitable agricultural land were converted to forest and allowed to fully re-grow. (From Rhemtulla et al. 2009, used with permission).

Box 4—Strategies for increasing or maintaining carbon stocks in forests and wood products (McKinley et al. 2011)

Current knowledge and forest management strategies for increasing forest carbon:

- Avoiding deforestation retains forest carbon and has many co-benefits and few risks.
- Afforestation increases forest carbon but can decrease stream flow and biodiversity, depending on where and how afforestation occurs.
- Decreasing harvests can increase species and structural diversity but may cause harvesting elsewhere and the risk of carbon loss from disturbance.
- Intensive silviculture can increase both forest carbon storage and wood production; however, practices can –reduce stream flow and biodiversity.
- Use of biomass energy from forests can reduce carbon emissions but would require more intensive forest management over broader areas.
- Substituting wood products for concrete or steel building materials can reduce fossil fuel emissions, but the potential carbon savings for the U.S. is not well known.
- Urban forestry has a small role in sequestering carbon and may improve energy efficiency of structures.
- Fuel treatments lower forest biomass to reduce wildfire risk and intensity, trading current carbon stocks in forests for the potential of avoiding larger carbon losses from future wildfire.
- Forest health treatments reduce susceptibility to drought, insects, and disease.

Some issues to consider when assessing mitigation options:

- What are the boundaries of the analysis—geographic, temporal, ownership, accounting, etc.?
- What are some likely strategies to increase carbon sequestration and reduce carbon emissions?
- What may be an optimum mix of mitigation options for a particular region, ownership, or parcel?
- What tradeoffs need to be considered between carbon management and management for other ecosystem benefits and services?
- How can this information be integrated into forest planning?

fertilization, air pollution, and natural disturbances are the same as in the recent past. Because only live aboveground carbon was estimated in this study, estimated potential gains are likely lower than what is actually possible. However, because of industrial wood use in the region and continued need for agricultural products, it is unlikely that the maximum potential gains in ecosystem carbon will be realized.

For this report, the magnitude of potential increases in carbon stocks was calculated by examining the age-class distribution of current forests, matching ages with productivity estimates from standard carbon yields for the region (Smith et al. 2006), and calculating carbon gains as if all existing forests were allowed to grow without natural disturbances or harvesting. This is not a recommended management scenario, but it is useful to put an upper bound on how much additional carbon could be sequestered in the future. Table 8 shows the results of the simulation over 50 years for the five most common forest types in northern Wisconsin. For all forest types combined, ecosystem carbon could increase at an annual rate of 4.3 Tg per year in the absence of harvest compared with the current rate of 1.5 Tg per year (Fig. 5), for a potential net additional increase of 2.8 Tg per year.

Table 8.—Mitigation potential of northern Wisconsin forests, 50-year no harvest simulation, by forest type

	Forest type					
Estimate	White-red-jack pine	Spruce-fir	Oak-hickory	Maple-beech-birch	Aspen-birch	Total
Total C 2007 (TgC)	82.57	198.56	143.39	363.81	234.25	1022.58
Total C 2057 (TgC)	106.48	219.06	186.69	439.29	287.77	1239.29
Annual change C ($TgCyr^{-1}$)	0.48	0.41	0.87	1.51	1.07	4.33
Annual products C ($TgCyr^{-1}$)						0.50
Net annual change C ($TgCyr^{-1}$)						3.83

Increasing Carbon Stocks in Forests and Wood Products

Increasing carbon stocks may involve several approaches including changing forest management practices, managing wood products, and increasing the area of forests. An overview of literature describing each of these strategies is presented here. Each of these strategies has potential benefits, tradeoffs, and risks, and may be an effective strategy if regional circumstances are appropriate.

Afforestation

An increase in forested land results in additional carbon sequestration over a landscape or region if new areas are converted or restored at a higher rate than deforestation (Sedjo 2001), though the timing and magnitude of impacts from the two activities means that carbon losses from deforestation (particularly aboveground biomass) occur much more rapidly than carbon gains from afforestation or reforestation (Intergovernmental Panel on Climate Change 2000). The recent rate of reforestation and afforestation in the United States may be as high as 700,000 ha per year (Masek et al. 2011), which is similar to the rate over the entire 20th century (Birdsey and Lewis 2003). These large increases are responsible for a relatively stable area (about 304 million ha) of U.S. forests over the last century after accounting for deforestation (Smith et al. 2009). Many Midwestern states had increases in the area of forest land over the last decade, including Wisconsin with an increase of 9 percent since 1977.

The appeal of increasing forest area as a mitigation strategy is evident in that 83 percent of the forestry projects reported to the U.S. Department of Energy's 1605(b) program involved tree planting (Energy Information Administration 2006). To qualify for credit from tree planting projects, the carbon sequestered must be an additional amount to what would have been there without the afforestation/reforestation project. This is usually easy to document since the alternative nonforest land uses typically store much less carbon per unit land area (McKinley et al. 2011).

A meta-analysis of the effects of land use change on soil carbon concluded that conversion of native forest to cropland decreased soil carbon by 42 percent on average (Guo and Gifford 2002). However, reversion of cropland to secondary forest may reverse this historical loss. Post et al. (2004) indicate that the average rate of soil carbon accumulation for afforestation and grassland establishment ranges from 10 to 40 g per m^2 per year (equivalent to between 0.1 and 0.5 percent per year), with the highest rates in more humid regions.

Midwestern states have significant nonforest areas that can be afforested if the value of carbon rises sufficiently, according to macro-economic analyses (Lewandrowski et al. 2004, U.S. Environmental Protection Agency 2005). Among different mitigation options, afforestation becomes a dominant strategy at prices ranging from $30 to $50 per ton of CO_2, with the Lake States and Corn Belt figuring prominently among U.S. regions with significant areas of marginal cropland and pasture available.

A study of afforestation opportunities in the Midwest (not including Wisconsin) by Niu and Duiker (2006) showed significant potential in Michigan, especially in the northern Lower Peninsula. They estimated that 24 percent of the agricultural land identified as marginally productive for crops could be available. Rhemtulla et al. (2009) came to a similar conclusion for the state of Wisconsin where there is a potential for increases in the area of forest land on marginal cropland in central northern Wisconsin.

Areas of marginal cropland and pasture that could be converted to forest are more likely to be found in those counties with 21 to 80 percent forest cover in the transitional area between northern and southern Wisconsin. Afforestation options are much more limited farther north because that area is already primarily forested, and nonforested areas include many open wetlands and pine barrens. Both of these ecosystems are highly valued ecologically, so afforestation efforts here may compete with other land management goals. To summarize, available land for afforestation is mainly on limited areas of private lands in northern Wisconsin. The Chequamegon-Nicolet National Forest (CNNF) is already 94 percent forested, and there is currently no significant backlog of needed reforestation.

Changing Forest Management Practices

There is a great deal of interest aimed at forest management and its potential for climate mitigation (Birdsey et al. 2006, Ruddell et al. 2007, Sedjo 2001). Management practices may affect the amount and structure of tree stems and crowns, the microclimate above and below ground, and the structure and chemical composition of the forest floor and soil (Jarvis et al. 2005). Since harvesting is usually involved, management also affects the amount of carbon stored in harvested wood products. Full accounting should include both changes in ecosystem carbon storage and harvested wood products. This section addresses management strategies or practices that may increase carbon stocks in forests and wood products of northern Wisconsin.

In general, increasing the interval between harvests in aggrading forests can lead to an increase in overall carbon storage; the greater the increase in the harvest interval, the higher the percentage increase in carbon storage (Ryan et al. 2010). Euskirchen et al. (2002) modeled nine different Great Lakes landscapes ranging in average age from 12 to 50 years with disturbance intervals ranging from 25 to 100 years. Results indicated the ecosystem with the longest rotation length of 100 years and oldest average age of 58.2 years was the strongest net carbon sink. The youngest ecosystem (with an average age of 15 years and managed on 25-year rotations) was the only ecosystem to act as a net ecosystem source, releasing carbon to the atmosphere. However, when the rotation age for this young ecosystem was increased to 50 years, it became a net carbon sink with a carbon biomass increase of more than 100 percent. This study did not include estimates of carbon stored in harvested wood products, which would have reduced the size of the estimated additional carbon from lengthening rotations.

Nunnery and Keeton (2010) looked at the effects of both harvesting intensity and postharvest retention on forest carbon storage in the Northeast United States. They found a clear gradient of increasing carbon sequestration (total carbon stocks) as forest management intensity ranged from high (clearcut) to low (individual tree selection or no management). The no-management scenario had significantly higher mean carbon stocks than all other scenarios. Among active management scenarios, individual tree selection with high structural retention sequestered the greatest amount of carbon. Postharvest structural retention significantly affected carbon sequestration, but longer rotations still resulted in the largest carbon stocks.

In a study on the Missouri Ozark Experimental Forest, Li et al. (2007) compared three silvicultural treatments eight years after treatment: no harvest management (control); single-tree, uneven-aged management; and clearcut even-aged management. The no harvest control had the highest total carbon (all carbon pools combined) with 182 Mg per ha, compared with 170 Mg per ha for single-tree harvest and 130 Mg per ha for clearcut harvest. This study did not estimate carbon in the harvested wood products.

Peckham et al. (2012, 2013) used an ecosystem process model, Biome-BGC, and life cycle inventory data for wood and paper products to explore the effects of

BIOME-BGC

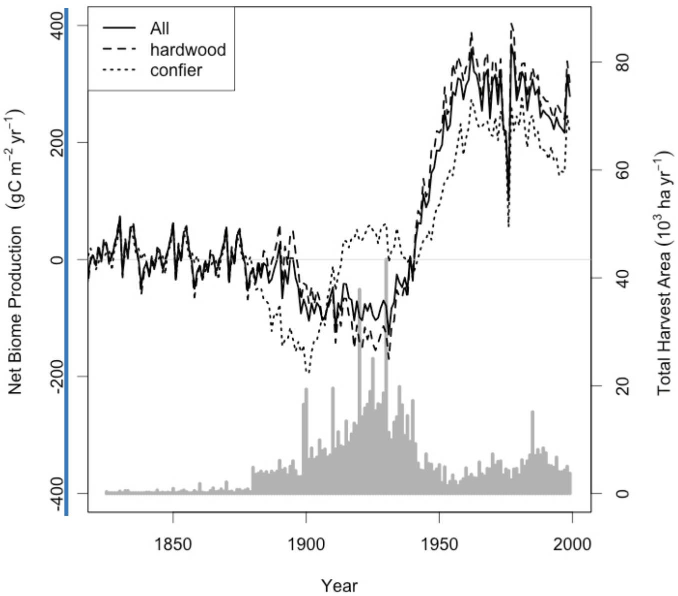


Figure 16.—Simulated net biome production (NBP) for the Chequamegon-Nicolet National Forest (CNNF) from Biome-BGC. Positive values indicate a C sink relative to the atmosphere. Grey bars show total harvest area.

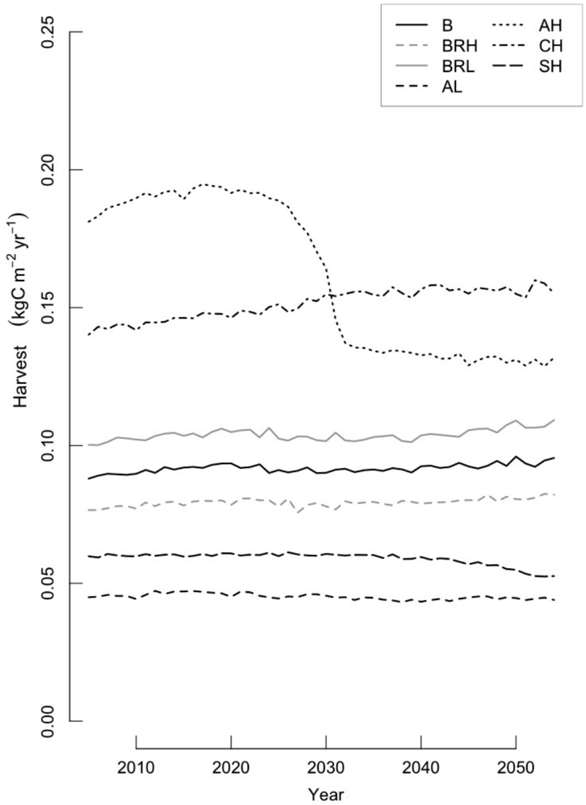


Figure 17.—Seven harvest scenarios for northern Wisconsin (Peckham et al. 2013): base = 25 percent clearcut and 75 percent selective cut over 1.7 percent of area per year (B); base + low residue retention (BRL); base + high residue retention (BRH); 100 percent selective cut (SH); 50 percent clearcut and 50 percent selective cut (CH); doubled area harvested (AH); half area harvested (AL).

different harvest scenarios on net biome production (NBP) and wood product carbon for the Midwestern region including northern Wisconsin. Biome-BGC produces a similar reconstruction of historical patterns of productivity as the InTEC model described earlier (Fig. 16). Seven harvest scenarios were simulated by varying the amount of harvest residue retained, the total harvest area, and the harvest type (clearcut and selective) to assess the potential impacts on NBP, net primary production (NPP), and total vegetation carbon (Fig. 17). The seven harvest scenarios removed from 11 to 38 TgC per year, with five scenarios resulting in increases of vegetation carbon of at least 12 percent, and the two most intensive harvest scenarios showing decreases of more than 8 percent (Fig. 18a). All harvest scenarios resulted in decreased NPP for the region (Fig. 18b). NBP was positive (i.e., carbon sink) but decreased in magnitude over the 50-year simulation period (Fig. 18c). More intensive management scenarios decreased average NBP by a maximum of 58 percent and vegetation carbon by a maximum of 29 percent compared to the current harvest regime (base scenario), while less intensive harvest scenarios increased NBP.

The results from Peckham et al. (2013) suggest that a reduction in the harvest area and the proportion of area harvested by clearcutting would increase vegetation carbon and NBP, and that decreasing the amount of residue removed could also increase NBP. However, these results are regional averages and may not be applicable to smaller areas or individual stands with different age structure and disturbance history.

Peckham et al. (2012) reported that for the CNNF, a slight increase in harvest area would maximize carbon sequestration over a 100-year period (Fig. 19). Simulated total NBP (i.e., cumulative carbon sequestered) ranged from 1.1 to 2.0 MgC per ha per year for annual harvest rates of 0 to 5 percent of the total CNNF area. Current percentages of clearcut and selective harvests in CNNF (20 and 80 percent, respectively) were held constant

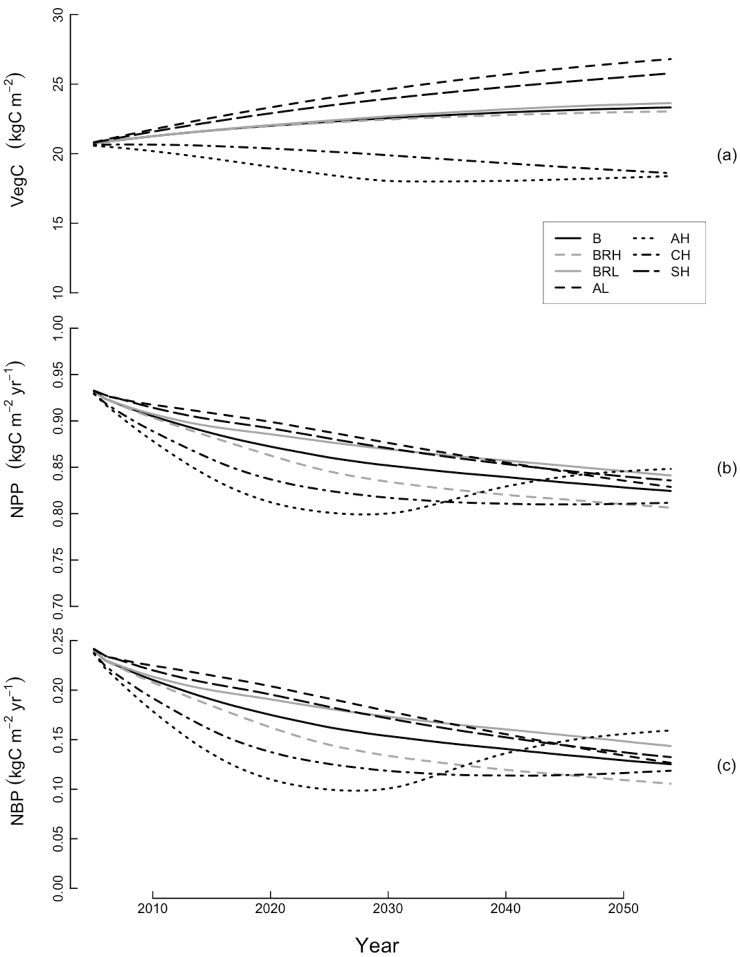


Figure 18.—Model results of (a) vegetation C (VegC); (b) net primary production (NPP); and (c) net biome production (NBP) for the forests of the northern Wisconsin region (Peckham et al. 2013). Harvest scenarios are the same as shown in Figure 17. Results of the different management scenarios are denoted with different line types.

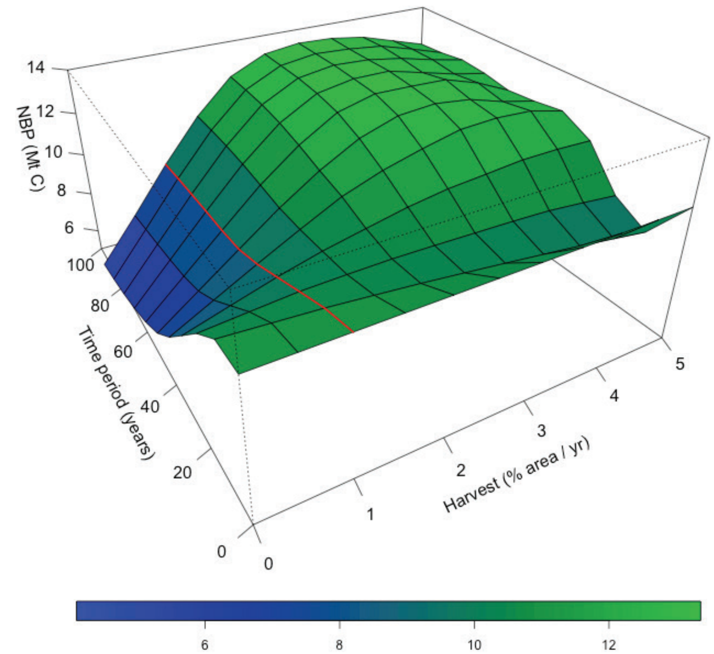


Figure 19.—Potential net C uptake for the Chequamegon-Nicolet National Forest (CNNF) in the next 100 years (Peckham et al. 2012a). The x-axis is the percentage of the total area of the CNNF harvested yearly, held constant in every year. The y-axis is the time horizon, or number of 10-year increments. The red line shows net biome production (NBP) when annual harvest is held constant at 1 percent of the CNNF area.

throughout the simulation. The 1 percent harvest area scenario represents approximately 50 percent of the allowable sale quantity set by the CNNF Land and Resource Management Plan (U.S. Forest Service 2013a). Increasing harvest intensity temporarily decreased NBP, but increased NBP in the long term because a greater proportion of the forest area was of optimal age for maximum NPP. Maximizing net carbon uptake over the 100-year simulation period increased NBP by 22 percent or 0.33 MgC per ha per year relative to the 1 percent harvest area scenario when harvest intensity in each time period was allowed to vary between 0 and 2 percent (within the limits of the CNNF plan).

Fissore et al. (2010) asked a different forest management question for the Upper Midwest. What is the potential effect of increasing the stocking of understocked forests? Understocked forests are forests with poor stocking primarily because of poor site conditions or pests. Their findings for Wisconsin, based on a rate of increased stocking of 29 Mg C per ha per year, resulted in a maximum potential of 3.2 TgC per year of increased sequestration, which is more than the current rate of 1.5 TgC per year of carbon sequestration in northern Wisconsin, but not likely achievable in a realistic scenario.

The previous analyses did not include effects of harvest on soil carbon. Soil contains the largest carbon pool in forest ecosystems (Pan et al. 2011a, Post et al. 1990), so changes in soil carbon should be considered when estimating carbon fluxes. For the North Central region, Heath et al. (2003) estimated that 60 percent of the total carbon in forests was in the mineral soil and about 8 percent in the forest floor in the year 1997. Grigal and Ohmann (1992) found that most terrestrial carbon in the Lake States is stored in the upper meter of mineral soil (55 percent) and the forest floor (9 percent). Powers et al. (2005) reported some carbon and nitrogen loss in the top 20 cm of soil in the first 10 years following harvest, but only when the entire forest floor was removed. Mixing the forest floor with the mineral soil, such as when disking to prepare a site for planting, may accelerate decomposition and mineralization of the organic layers (Jarvis et al. 2005, Pritchett and Fisher 1987). However, Alban and Perala (1989) found that heavy disking for natural regeneration of paper birch did not change total soil carbon over a 7 year period. Comprehensive literature reviews reveal that the results of harvesting and soil mixing are highly variable, though many studies suggest that harvesting has a significant effect on the forest floor but not mineral soil (Johnson and Curtis 2001, Nave et al. 2010). Thus, operations that minimize soil disturbance may or may not increase the net strength of the carbon sink, probably depending on local factors such as climate and nature of the forest operation.

Peckham and Gower (2011) used the ecosystem process model Biome-BGC to simulate the effects of harvest and residue removal management scenarios on soil carbon, available soil nitrogen, NPP, and net ecosystem production (NEP) in jack pine (*Pinus banksiana* Lamb.) and sugar maple (*Acer saccharum* Marsh.) ecosystems in northern Wisconsin. All the harvest scenarios decreased mineral soil carbon and available mineral soil N content relative to the no harvest scenario for jack pine and sugar maple. These studies all suggest that harvest effects on soil carbon could be important when evaluating the effects of harvest on ecosystem carbon stocks.

In summary, changing forest management practices has complex and long-lasting effects on the stocks and fluxes of carbon, and it is not always possible to predict the results from a given project, although the results of many projects may have a positive effect over a large landscape, on average. It is difficult to recommend specific management practices, though there seems to be some consensus in the literature relevant to northern Wisconsin that: (1) lengthening harvest rotations will increase carbon stocks if other disturbances do not occur; (2) there is an optimal harvesting rate that maximizes annual carbon sequestration (but not necessarily carbon stocks); (3) low-intensity harvesting (selective harvest) appears to result in both higher carbon stocks and higher carbon sequestration compared with no harvest and minimizes disturbance to the forest floor and soil; and (4) if biologically feasible, increasing the stocking on poorly-stocked forest land will increase both carbon stocks and sequestration. In all of the cases involving harvesting, accounting for the carbon in harvested wood products increased the overall carbon stocks but not enough to fully offset the reduced carbon stocks on the land. These conclusions illustrate that there appears to be multiple solutions to managing for carbon, either through increasing productivity, storage, or both.

Fire and Fuels Management

Fire plays an important role in global and regional carbon budgets. It is a primary mechanism for the loss of stored terrestrial carbon and can emit large quantities of carbon dioxide to the atmosphere. On a regional and global scale, fires have been shown to account for a large portion of annual variation of CO_2 emissions to the atmosphere (Randerson et al. 2005, Schultz et al. 2008). In the Lake States, fire has had less impact on forests in recent years compared with other regions of the United States (Birdsey and Lewis 2003, Zheng et al. 2011). This was not always the case. In the North Central region, wildfire was much more significant in the late 19th century and early 20th century, a period of rapidly increasing logging before fire control programs were established (Sterns 1997). Before the advent of intensive logging, fire return intervals ranged from about 50 years for jack pine to more than 1000 years for some hardwood forests (Frelich 1995).

Fuel treatments, such as reducing tree density by thinning, may reduce the intensity and extent of future wildfires (Finney 2001). Because moderate to heavy thinning lowers the carbon stored in the forest and, in some cases, removes an amount of carbon comparable to a stand replacing wildfire (Mitchell et al. 2009, Stephens et al. 2009), it is important that such activities fully consider the probability of a stand replacing wildfire (Ryan et al. 2010). In the Lake States, prescribed burning may reduce ecosystem respiration and preserve carbon stocks. Noormets et al. (2007) studied carbon flux on the Moquah Barrens, an extensive pine barrens restoration area on the CNNF, and found that the fire-maintained pine barrens had lower ecosystem respiration rates than the young, harvest-generated hardwood and red pine stands which had high amounts of logging residue.

Gough et al. (2007) examined the effects of clearcut and slash burning on carbon storage in a mixed deciduous forest in the northern Lower Peninsula of Michigan. Although stands that were repeatedly disturbed reverted to sinks within 6 years of disturbance, repeated disturbances (a second harvest and burn) reduced site quality and resulted in annual carbon storage that was 45 percent lower than that in the reference stand receiving a single harvest and burn disturbance. Maximum annual carbon storage was 26 percent lower than that in the reference stand over a 62-year period. Another study by Gough et al. (2008) measured annual forest carbon storage from 1999 to 2005 in a mixed deciduous forest in Michigan's northern Lower Peninsula, dominated by aspen and subjected to harvest and fire, and found lower annual carbon sequestration and lower carbon stocks in forests having more frequent disturbances. These reductions, from roughly 2 to 1 MgC per ha per year, were attributed to reduced soil fertility.

In summary, the effectiveness of using fire-related mitigation options to increase carbon stocks over the long term is highly uncertain. Reducing fuels through mechanical treatment or biomass harvesting may result in reduced emissions if frequency of future wildfires is reduced. One viable option may be to maximize utilization of woody material before conducting prescribed burns, but the studies referenced above did not include estimates of carbon stored in harvested wood products.

Managing the Industrial Forest Carbon Cycle: Harvest, Transportation, Processing, and Final Fate

Carbon emissions occur during harvest and processing of timber, and carbon stored in wood products is gradually released through decomposition and combustion. Since not all of the harvested carbon is released immediately to the atmosphere, the amount remaining in products is temporarily stored. In addition, forest products may require less energy to produce than materials such as concrete and metal, resulting in a net reduction of carbon emissions that can be substantial according to some estimates, as illustrated in Figure 8 (Krankina and Harmon 2006, Lippke et al 2004, Perez-Garcia et al 2005). However, very few studies have quantified the full effects, including substitution, of using wood products on the carbon cycle, since the data requirements are extensive and the accounting rules for substitution effects are not very well established. Box 5 summarizes some potential mitigation options involving the industrial wood carbon cycle.

Box 5—Summary of industrial carbon cycle mitigation options

- Consider total fuel consumption when planning hauls roads and skidding/forwarding patterns.
- Incorporate fuel consumption considerations when planning thinning regimes in even-aged management systems.
- Substitute wood for cement or steel which uses more energy to extract and process.
- Increase lifespan of wood products in order to retain carbon in long-lived wood products.
- Increase energy efficiency in mill processing, which will substantially decrease carbon emissions.
- Reduce the distance that raw material is transported (e.g., to mills) in order to decrease carbon emissions from transportation.
- Buy local wood fiber thereby avoiding extremely long transportation chain emissions.

White et al. (2005) analyzed the industrial and biological effects of timber production on the carbon cycle for northern Wisconsin forests. Their wood products analysis included fossil fuel used in harvesting, transport, and manufacturing processes, but did not include the effects of substituting wood for other products. They found that emissions from harvesting for the CNNF were -0.10 MgC per ha per year, a small carbon emission source. The nonindustrial private forests had emissions of -0.11 MgC per ha per year, and the state forests were the highest emission source at -0.18 MgC per ha per year. Coupling these results with the biological carbon cycle, however, indicates that the CO_2 emissions associated with the industrial carbon cycle are more than offset by the net CO_2 uptake of the forest (Gower and Ahl 2006; Peckham et al. 2012).

Substituting wood products for nonwood products that require more energy to produce, such as steel and concrete, may reduce net C emissions (Hennigar et al. 2008). While some studies have calculated avoided emissions (Lippke et al. 2004, Perez-Garcia et al. 2005), obtaining such estimates is not straightforward and involves a number of assumptions and uncertainties (Miner and Perez-Garcia 2007). Even lacking precise data, it is nonetheless important to consider the potentially significant effects of product substitution because the estimated net reduction in emissions from wood substitution can be significant (Sathre and O'Connor 2008). Opportunities for substitution in the United States are largely in nonresidential buildings (McKeever et al. 2006, Upton et al. 2008) because most residential housing units are already built with wood.

Avoiding Loss of Forest Land

Loss of forests causes significant carbon emissions. Forest conversion not only releases CO_2 but significantly decreases the capacity of a site to sequester additional carbon in the future (Ingerson 2007). Deforestation in the United States has recently affected about 355,000 ha per year (Masek et al. 2011). Estimated carbon losses from deforestation in the United States are approximately 23 TgC per year based on analysis from1987 to 1997 (Birdsey and Lewis 2002) and equate to more than 10 percent of the net increase in carbon stocks on existing forest land. Zheng et al. (2011) estimated that for all of Wisconsin, loss of carbon stocks from deforestation was 1.3 TgC per year from 1992 to 2001 based on a loss of forest area of about 16,000 ha annually. Generally, more than half of the forest area loss in the Lake States is to urban or suburban development and other developed uses (Birdsey and Lewis 2002).

Because the area of Wisconsin forests increased from 1983 to 1996 and has been stable since then (Perry et al. 2008), deforestation may not be perceived as a significant problem in the state. However, these are net change statistics and do not clearly reflect losses of forest area and carbon stocks to deforestation, which have been more than offset by afforestation of marginal cropland. Over the long term, patterns of housing density change suggest that deforestation is both a significant issue and an opportunity for action to reduce emissions of greenhouse gases. However, reducing the loss of forest land to developed uses is challenging because of the strong leakage effect—it is very difficult to ensure that preserving one area from forest loss will not simply result in forest clearing in another area (Murray et al. 2004).

Northern Wisconsin is an amenity migration destination, so-called because its natural beauty and outdoor recreation opportunities attract residents (Stewart 2002). Amenity migrants are primarily retirees, sometimes converting their summer home to a year-round or two-season home. The social outcomes of migration are mixed; new residents are new property taxpayers in these rural communities, and often bring with them a stream of income originating outside the area that represents new economic activity for the rural economy. The addition of year-round residents helps to even out the seasonal cycles that characterize tourism-based economies, which in turn supports more year-round employment that can provide young workers the opportunity to stay in their home community (Johnson and Stewart 2007).

The most significant impact of amenity migration is that it creates demand for housing. Areas like northern Wisconsin have experienced decades of housing growth (Hammer et al 2004, Radeloff et al. 2005a). Housing development occurred first around lakes and in small

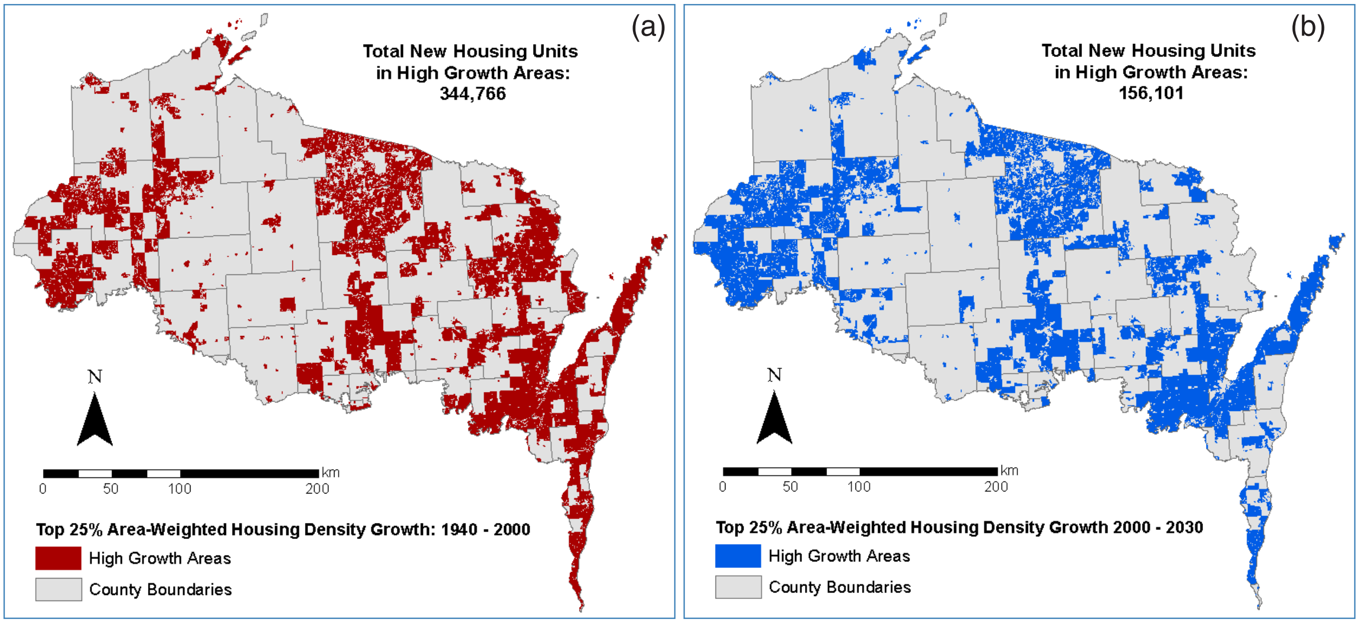


Figure 20.—Regions of (a) fastest housing growth between 1940 and 2000, and (b) projected fastest housing growth between 2000-2030.

towns then pushed into the forests and the countryside in recent decades when lakeshores were unavailable or unaffordable (Gonzalez-Abraham et al. 2007, Hammer et al. 2009). Both patterns of growth expand the wildland-urban interface (WUI) where homes are near or within forests and other areas with wildland vegetation (Radeloff et al. 2005b).

The impacts of housing are numerous. Trees are cut to make space for homes, removing biomass from the forest. The built surfaces that replace trees have higher reflectance and most are impermeable. Houses create openings and edge habitat, support predation and harassment of wildlife, and influence invasion of exotic plants into the forest. New roads accompany housing growth and have similar extensive and well-documented effects (Hawbaker et al. 2005, 2006). While few of these impacts are catastrophic or abrupt, they are persistent and widespread, raising concern about effects that accumulate over space and time.

The Land Cover Impacts of Housing Growth

To examine in detail when and where housing growth has occurred and is likely to occur in the future, we used Census housing data to estimate historic patterns and project future housing at a subcounty scale (see Hammer et al. 2004 and Hammer et al. 2009 for methods). These data show where housing growth was fastest between 1940 and 2000 and where the most growth is expected in coming decades from 2000-2030 (Fig. 20). The high growth areas represent the neighborhoods (partial block groups or PBGs) with the top 25 percent of housing density increases. These high-growth PBGs contain 86 percent of all the new housing units added between 1940 and 2000 and 82 percent of the new units expected by 2030. The map in Figure 21 shows the top quartiles of the two growth periods, with PBGs in the top growth

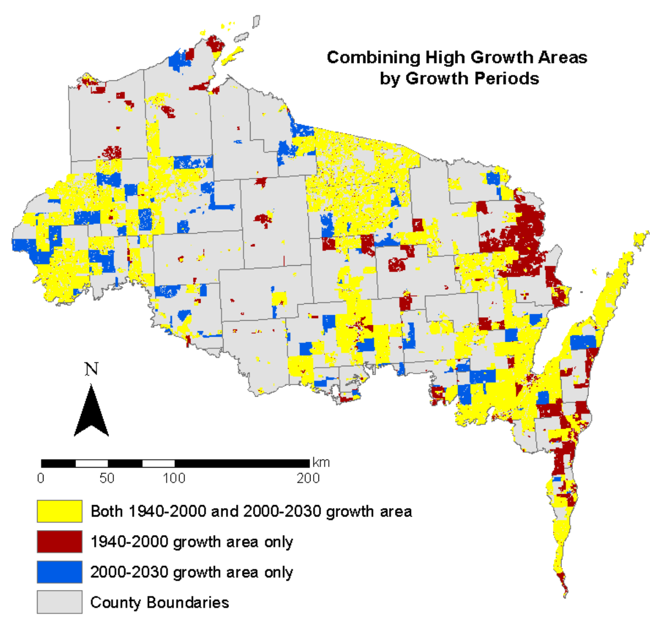


Figure 21.—Changing patterns of housing growth, northern Wisconsin.

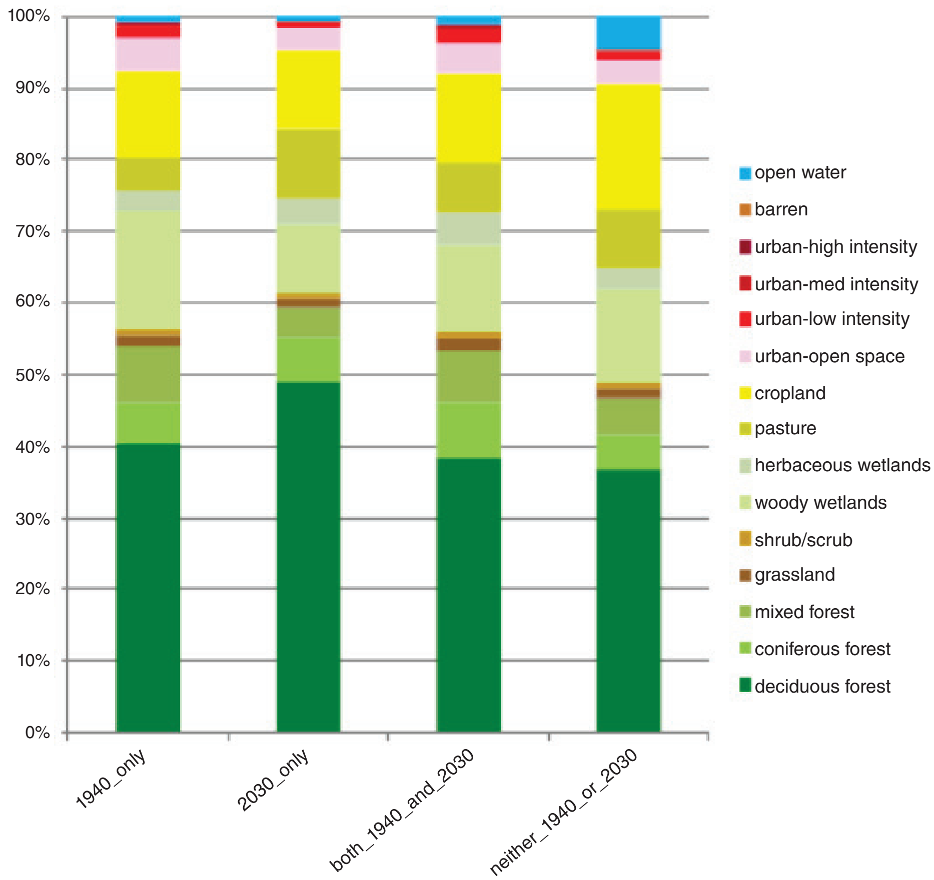


Figure 22.—Land cover proportion by housing growth category, northern Wisconsin.

category during both periods shown in yellow. The housing growth rate was 244 percent between 1940 and 2000, and we expect 128 percent more growth between 2000 and 2030.

The carbon consequences of housing growth depend in part on what type of vegetation is affected by development. To assess this, we overlaid maps of historic and future high housing growth on the 2001 National Land Cover Database (NLCD) (Homer et al. 2007) and summarized the areas in these PBGs by land cover type. Note that housing development is unlikely to affect the entire PBG; this analysis simply indicates the land cover characteristics of the neighborhoods experiencing the most growth. It is also important to note that the land cover that was displaced by initial development (e.g., in 1940 and subsequent decades) may have been different than the vegetation present now; without detailed and extensive land cover data from the 1940s, we cannot know the extent of differences. Figure 22 shows the land cover types represented in the four groups of PBGs: those that grew from 1940-2000; areas forecast to grow between 2000 and 2030; areas in the top quartile of growth in both periods; and those with no fast growth in either period. All reflect the character of northern Wisconsin's landscape, with forests and other wildlands covering over half the area.

Reducing the Projected Impacts of Housing Growth

The land use projections described here are based on an econometric model that simulates changes in land use as a function of the changing profitability of various land uses, and the costs of making a change in land use (Radeloff et al. 2012). Profitability, or net returns, is determined by the productivity of the land, its location, and the production costs associated with its use, including those needed to change its use. In other words, the model assumes that landowners make decisions about land use based on the relative profitability of different land uses. In this way, the model uses observations of previous landowner decisions to estimate the probabilities of future decisions in terms of the land use categories gaining or losing area. Both taxes and subsidies are policy instruments that aim to alter land use outcomes either by encouraging transition into a particular land use, or by discouraging transition out of a favored use. The scenarios tested here are examples of such policies.

Land use transition data was from the Natural Resources Inventory (NRI) for 1992 and 1997 (Natural Resources Conservation Service 2009) in which field surveys of a nationwide sample of plots on non-Federal lands from the 2 years were compared. Note that the NRI uses a different sampling scheme for all lands than the Forest Inventory and Analysis (FIA) program uses for forest lands, so in some regions there are differences in the resulting estimates of the area of forest. Land use was derived from the 2001 NLCD dataset (**NLCD 2001**) (Homer et al. 2007) aggregated to 1 ha pixels, and classifications were grouped into five categories: urban, forest, crops, range, and pasture. The Protected Areas Database (PAD) (U.S. Geological Survey 2013) was used to identify public lands, and these remain unchanged in future projections. Land capability, a measure of potential productivity, was based on the USDA National Resources Conservation Service Soil Survey Geographic Database (Natural Resources Conservation Service 2011) classified into four nonirrigated classes. We tested three scenarios (two that retain forest, one that retains forest and rangeland) and compared them to a baseline scenario (**Baseline**). A forest tax and subsidy (**Forest1**) provided a $100/acre subsidy for land entering forest use, and a $100/acre tax for land leaving forest use. A forest tax only (**Forest2**) imposed a tax of $100/acre for land transitioning from forest use. Both **Forest1** and **Forest2** were afforestation scenarios intended to retain or move more land into forest use. Finally, the native scenario (**Native**) imposed a $100/acre tax for land leaving forest or rangeland. Its intent was to retain land in natural land uses (forest or range) versus intensively human-dominated land uses, in an effort to preserve natural habitats.

Land use change is simulated stochastically for 50 years (Lewis and Plantinga 2007). Each NRI plot is assigned a transition probability based on observed changes in its land use, location, potential productivity, and other factors representing its profitability for each land use as well as costs of changing land use. Transitions into or out of land uses are simulated by comparing each plot's transition probabilities for all possible land use changes with a random number between zero and one, to determine which will occur (e.g., given a 40 percent probability of remaining forest and a 60 percent probability of becoming urban, will it become urban or not?). This simulation is iterated 500 times to account for the stochastic variability of outcomes in the real world, and results are aggregated to the subprovince level.

Thus we create a probability-based estimate of projected land use, one which is based on observed landowner behavior in response to market prices. The baseline scenario results show expected patterns of land use if the policy environment does not change. Comparing the four sets of scenario-specific projections illustrates the different outcomes predicted under various tax and subsidy policies.

In northern Wisconsin, the baseline and the alternative scenarios for future land use predict an increase in range, a major loss in pasture, a smaller loss in crops, and major gains in urban land use (Fig. 23) (Table 9). These outcomes are unsurprising in that the profitability of urban land use is so much higher than that of other land uses that the taxes and subsidies tested here do little to discourage urban conversions. The inverse is true of pasture and crop lands; both are lower-return land uses that are unsupported by the taxes and subsidies we tested. Relative to forests (or in the native scenario, forests plus range lands), the returns associated with pasture and crop uses are decreased by these policies, making transition to other land uses more likely. Forest land use increases only under the forest tax and subsidy scenario. In terms of the relative changes this model predicts, the increase in urban use and decrease in pasture use are most notable and consistent across all policy scenarios.

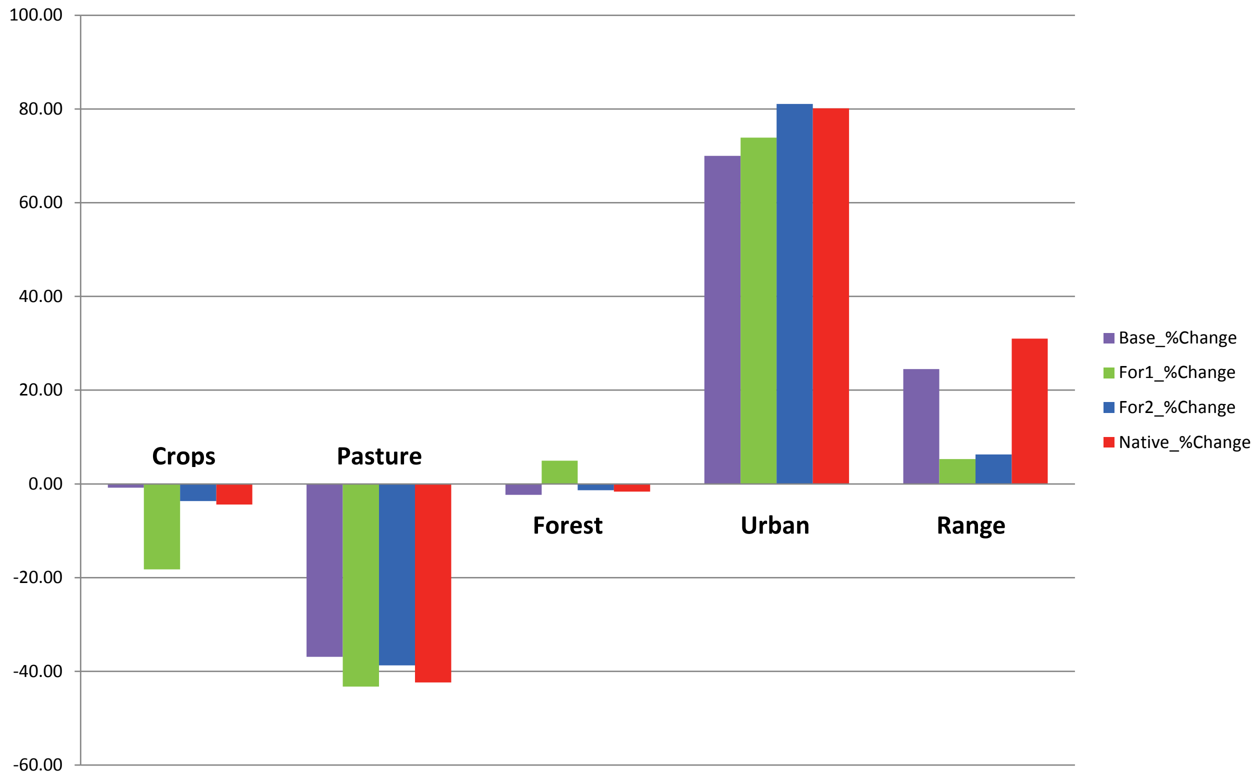


Figure 23.—Projected percentage change in future land use calculated as the percent change in the National Land Cover Database 2001 land area in northern Wisconsin, by future land use scenarios: a baseline projection (Base), a forest tax and subsidy scenario (For1), a forest tax only subsidy (For2), and a tax incentive to preserve native vegetation (Native).

Table 9.—Land use by scenario

	NLCD 2001[a]	Baseline 2051	Forest1 2051	Forest2 2051	Native 2051
			Area (ha)		
Crops	1,261,998	1,251,977	1,031,876	1,215,542	1,206,290
Pasture	601,102	379,364	341,071	368,504	346,351
Forest	3,839,139	3,750,043	4,028,903	3,787,738	3,776,719
Urban	393,062	668,155	683,534	711,742	707,987
Range	186,950	232,712	196,867	198,725	244,904
			Raw area change (ha)		
Crops	0	-10,021	-230,122	-46,456	-55,708
Pasture	0	-221,738	-260,031	-232,598	-254,751
Forest	0	-89,096	189,764	-51,401	-62,420
Urban	0	275,093	290,472	318,680	314,925
Range	0	45,762	9,917	11,775	57,954
			Percent change in area		
Crops	0	-0.79	-18.23	-3.68	-4.41
Pasture	0	-36.89	-43.26	-38.70	-42.38
Forest	0	-2.32	4.94	-1.34	-1.63
Urban	0	69.99	73.90	81.08	80.12
Range	0	24.48	5.30	6.30	31.00

[a] See text for a description of each scenario.

Effectiveness of Policies to reduce Housing Growth

Our results show that while there will most likely be fairly substantial changes in land use, the differences in future outcomes under alternative policy scenarios were relatively small. Policy scenarios within a region like northern Wisconsin will be most effective when two conditions are met: (1) land prices across land use categories must be **similar**, and (2) land that can change uses must be **available** (i.e., unrestricted by public ownership, not too costly to convert, and of comparable value to target land uses).

If land uses are similar in profitability so that a small change in price can alter which category is the highest and best use for land, then taxes and subsidies set at modest levels can be effective. If there is a major difference in profitability such that one land use generates a much higher return on investment, taxes and subsidies must be set at higher levels to change the relative profitability across land uses. Urban compared to nonurban land uses illustrate a wide disparity in profitability. Urban land use generates so much higher returns that policy changes have to be dramatic to overcome the large price difference to the next highest-return category.

Land availability matters, especially within a small region. If a policy increases the profitability associated with forested land, afforestation will only result if there is also land available that can support additional forest growth. In northern Wisconsin, the limited response to afforestation scenarios (Forest1 and Forest2) is due in part to the relative scarcity of privately owned land not already forested. It would be cost prohibitive to bring remaining private lands into productive forestry use. Hence the model shows little change in expected forest trends; urban land use will increase under all four scenarios, regardless of policy changes intended to favor forest land use.

Because of its dominance in the baseline and all of the tax and subsidy scenarios, it is worth examining urban land use more closely. The urban land use category is unique in that it describes the dominant use of the land, but is not precise about its cover, particularly in an area like northern Wisconsin where most urban development is construction of homes driven by amenity migrants wanting a summer retreat or retirement home in the woods. Homeowners usually retain trees for privacy and aesthetics.

Once land becomes urban, it does not change use. The NRI data do not record any transitions out of urban use. This is not surprising given the relative permanence of the built environment and the time period of these data from the early 1990s, when housing growth was reaching all-time high rates. The practice of removing housing from urban lands is still unusual, though occurring more widely after the housing bust of 2008. Hence projections under all scenarios show only growth in urban land use.

In summary, the effectiveness of policies intended to alter land use change outcomes by imposing taxes and subsidies depends on the relative profitability of land uses and the availability of land that can undergo land use change. While northern Wisconsin currently has extensive forested land, it is likely to have less private land in forest cover in the future, and taxes and subsidies at the moderate levels tested here can do little to retain or increase forest land cover. Therefore, we conclude that the policies considered here are not likely to have any significant effect on the expected continued loss of carbon in forests as development occurs, estimated at 1.3 TgC per year for the whole State of Wisconsin.

Increasing Use of Wood for Bioenergy

Forest-based bioenergy is increasingly being examined as an option for greenhouse gas mitigation. Some studies show that in comparison to fossil fuels, biomass results in lower emissions when used to create heat, electricity, and transportation fuels (Keoleian and Volk 2005, Malmsheimer et al. 2008, U.S. Environmental Protection Agency 2007). Other studies, however, are skeptical of the carbon benefits, citing uncertainties in the estimates and lack of full accounting for factors that may reduce the expected benefits. Woody biomass from sustainably managed forests is often considered "carbon neutral", meaning that emissions are simply not counted. However, some net emissions may occur during the biomass production life cycle, and there could be some significant secondary effects such as off-site changes in land management (Cherubini et al. 2011, Wise et al. 2009). Bird et al. (2012) demonstrated that the current Intergovernmental Panel on Climate Change (IPCC) accounting approach provides an incentive to use biofuel but does not adequately account for the reduction of carbon stock on the land. Searchinger et al. (2009) estimate that diverting U.S. corn from food to biofuel production actually increased net emissions to the atmosphere due to leakage effects on land use change.

There is substantial woody biomass available in the United States. The U.S. Department of Energy (2011) estimates that if prices are high there could be a billion tons of dry biomass available from all sources, with 12 percent coming from forests. The main sources of forest biomass in addition to what is currently used for biofuel are wood residues (logging residues and thinnings) and urban wood wastes followed by pulpwood and mill residues. Significant quantities of wood biomass are available in the Lake States (Goerndt et al. 2012, U.S. Department of Energy 2011). One important constraint on the carbon benefits of using wood for biofuel is that the emissions from transportation may offset some or all of the potential benefit if the distance to transport the biomass from the forest to the facility is too long.

The potential to use a forest-based resource for energy production and greenhouse gas mitigation is relevant to the northern region of Wisconsin, which is more than 50 percent forested and contains more than two-thirds of the forests in the state (Wisconsin Department of Natural Resources 2002). Wisconsin already has a strong forest products industry, which employs nearly 100,000 people statewide and generates $30.8 billion in forest products related industrial output annually (Mace et al. 2004). Wood and wood waste is the most widely used renewable fuel in Wisconsin and makes up 4.6 percent of state energy consumption (Energy Information Administration 2009). This is higher than the national average of 2.5 percent of energy consumption from wood and wood waste.

Several factors are encouraging a greater use of wood for energy in the state, including concerns about mitigating greenhouse gases and climate change, increasing the amount of energy from domestic sources, and strengthening local and rural economies. Additionally, both national- and state-level policies are encouraging a greater use of renewable energy. Nationally, the Renewable Fuel Standard of the Energy Policy Act of 2005 and the Energy Independence and Security Act of 2007 mandated an increase in the amount of renewable transportation fuels through 2022, with significant increases in the amount of cellulosic ethanol produced nationally. Statewide, Wisconsin has enacted a Renewable Portfolio Standard which requires that by 2015 utilities produce 10 percent of their electricity from renewable energy sources, with biomass being one possible source. The Governor's Task Force on Global Warming (2008) recommended a number of additional policies to encourage utilization of biomass from forest and agricultural sources for the purpose of greenhouse gas mitigation.

While the regional forest products industry has declined in recent years due to global economic factors, growth in the bioenergy economy in Wisconsin could significantly increase demand for biomass (Becker et al. 2009). A recent analysis of available forest biomass for energy uses in Wisconsin estimated that 1.7 million dry tons per year of forest biomass could be available when no financial constraints are considered, and 1.5 million dry tons per year could be available at a price of $40 per dry ton at roadside (Becker et al. 2009). The results of this analysis are similar to national-level estimates of biomass availability, which ranged from 0.6 to 2.3 million dry tons per year in Wisconsin (Willyard and Tikalsky 2006). While the existing demand for biomass for energy production was estimated to be 579,000 dry tons per year, a number of bioenergy projects have been announced that could nearly triple biomass demand statewide if all of the announced facilities are developed. The use of short-rotation woody crops, such as high-productivity plantations composed of aspen or willow species, could also provide a substantial source of biomass in the future.

Peckham and Gower (2012) used an ecosystem process model, Biome-BGC, combined with a collection of greenhouse gas life cycle inventory models to estimate availability of woody biomass feedstock from temperate forests in the Upper Midwest. Seven forest harvest scenarios in the biological ecosystem and three biofuel production scenarios in the industrial system were simulated for 50 years. The seven harvest scenarios produced a 3.5-fold difference in woody biofuel feedstock, ranging from 9 TgC for a reduced area harvest to 33 TgC for the increased area harvest scenario. The net system carbon balance for current management and product production was positive (i.e., carbon sink) and averaged 1.2 MgC per ha per year for the simulation period. The net system carbon balance was positive for most scenarios, but model results were sensitive to both the harvest scenario and the life cycle model emission factors for individual forest products. Net forest system carbon balance was significantly and negatively correlated (R^2 = 0.67) to biomass harvested, which illustrates the tradeoffs between increased carbon uptake by forests and utilization of woody biomass for biofuel feedstock.

The biomass described above is potentially available, meaning that it is present in the forest or at a facility and could theoretically be used for energy. However, the actual amount of biomass that is available will likely be less than what is potentially available. Constraints on availability include market conditions and prices, operational constraints, landowner willingness to harvest, and ecological considerations (Becker et al. 2009). A set of biomass harvesting guidelines developed for Wisconsin to help forest owners and managers address concerns related to forest sustainability (Herrick et al. 2009) encourages retaining woody biomass on some sites to minimize environmental impacts from biomass harvesting. Biofuels are currently uneconomical compared with fossil fuels, in the absence of incentives. Rosberg and Miranowski (2011) concluded that cellulosic ethanol production is not sustainable without significant incentives or sustained high oil prices in the range of \$135-\$170 per barrel. Thus at present, some form of incentive payment would be needed to increase biofuel use in the absence of other policy measures. A greenhouse gas price for biofuel offsets could serve as an economic incentive, but it has been estimated that the price of CO_2 would need to be at least \$30 per ton for biofuel offsets to become competitive (U.S. Environmental Protection Agency 2005). Finally, as mentioned above, accounting for greenhouse gas emissions from using woody biomass is also controversial and could affect its implementation as a mitigation option.

Climate Change and Other Risk Factors

Many of the current stressors that act upon the forests of northern Wisconsin are expected to increase as a result of climate change. Swanston et al. (2011) synthesized the available information on projected climatic change in northern Wisconsin and potential effects on forest ecosystems in order to assess the vulnerability of these forests to climate change. Temperature increases and altered precipitation regimes are expected to lead to drier summer soil conditions which may make drought and associated disturbances (such as pest and disease outbreaks and fire) more prevalent. Climate change is also expected to increase the frequency and severity of extreme weather events, which may lead to greater occurrence of catastrophic wind and rain events (Campbell et al. 2009, Dale et al. 2001, Swanston et al. 2011). Overall, shifting patterns among disturbances and stressors are expected to strongly influence ecosystem drivers, which will have follow-on effects on forest productivity and carbon sequestration.

Northern Wisconsin's location at the intersection of three major biomes may make forests particularly susceptible to climatic changes. Suitable habitat for tree species is expected to shift northward as the climate changes. Many of the area's dominant tree species are located at the southern extent of the species' range, and declines in the suitability of habitat may lead to subsequent declines in the ability of those species to persist in the region over time. Suitable habitat may become available for other species, although there may be lags before new species and forests are able to establish. Changes in productivity are possible in response to changing atmospheric conditions and weather and interactions with disturbances. Ecosystems that are dominated by boreal species, have low-diversity, are less resilient to changing conditions, or feature species that are already at risk or in decline may be the most vulnerable, while species and ecosystems that have contrasting characteristics may be better able to accommodate change and maintain productivity (Swanston et al. 2011).

POTENTIAL PATHWAYS TO IMPLEMENTATION

To the extent that land management creates additional carbon storage either on the land or in products, there may be opportunities for engagement in several different markets or registries, some of which give credit for offsetting emissions (see Box 6). However, there are multiple prerequisites to market participation, and these opportunities may be further constrained by economic, legal/policy, or other logistical considerations or barriers. This section outlines universal forest carbon accounting issues then describes participation options within the current policy landscape, highlighting opportunities and constraints specific to three carbon protocols and the developing national policy landscape. Finally, public policy with respect to land management mandates and potential for participation in market opportunities is considered.

Forest Carbon Accounting Issues

A universal component to any forest-based carbon project—be it afforestation, reforestation, improved forest management, or avoided deforestation and degradation—is dealing with several forest carbon accounting issues. The way in which these issues are defined and treated within a project protocol affects protocol credibility, the project enrollment process, and ultimately helps to define the atmospheric/climate benefits of a project.

Some of the most significant accounting issues for market participation are:

- **Additionality**—a project is considered additional if it would not have occurred absent the added incentives provided by the carbon market. This applies to both the economic and biological aspects of additionality.
- **Baselines**—the expected sequestration (or emissions) that would occur without the project (i.e., the "business as usual" scenario).
- **Leakage**—a shift in emissions reductions from a project to a location (or sector) outside of the project boundary. In the case of forestry, preserving one tract of forest may put added development pressure on an adjacent tract.
- **Permanence/Reversal Risk**—the potential that additional sequestration achieved may be reversed either intentionally or unintentionally (through human actions, fire, insects, disease, or weather).

Perhaps the most significant analysis and estimation issue involves establishing the boundaries of analysis for mitigation options or projects, especially for comparing among different alternatives including comparison of an action with a baseline. For example, if a no harvest scenario was considered the baseline, then the estimated additional effect of multiple-rotation harvesting

Box 6—What is an offset?

A greenhouse gas (GHG) offset is generated by the reduction, avoidance, or sequestration of GHG emissions from a specific project. Offsets are so named because they counteract or offset greenhouse gases that are emitted into the atmosphere; they are a compensating equivalent for reductions made at a specific source of emissions. Forest-based offsets are a specific kind of offset, and can take several forms:

- **Afforestation**—creation of new forests on land that has been unforested for a certain amount of time, typically ten or more years.
- **Reforestation**—restoration of forests on lands that were recently forested.
- **Active/Sustainable/Improved Forest Management**—activities that enhance carbon storage on a forested landscape or in wood products.
- **Reduced Emissions from Deforestation and Degradation (REDD)**—avoided emissions from protecting standing forest carbon stocks. This term is most often used to refer to international/tropical forest protection; in the United States, the relevant term is often "avoided conversion."

compared with the baseline would be positive or negative depending on whether or not the substitution of wood products for other materials was included in the analysis (see Fig. 8). Including leakage or not is another example of a boundary issue. Searchinger et al. (2009) highlighted the significance of this issue with respect to bioenergy. They showed how allocating additional land to bioenergy production would have significant effects on carbon emissions from conversion of intact forests to bioenergy plantations, thus disproving the common assumption that using renewable bioenergy is "carbon neutral". Indeed, the decision to include the secondary or tertiary effects of a project or action is among the most critical steps of an analysis.

It is important to note that any activity that increases carbon sequestration or storage by reducing harvest levels can result in increased harvesting elsewhere to compensate for the reduced forest products (another example of leakage). Similarly, the utilization of harvested materials, for biomass fuel or long-lived forest products, can affect the carbon storage benefit of forest management practices.

Markets and Registries

Within the past several years, various protocols and registries have emerged to define the "Over the Counter" (OTC) voluntary carbon market. In addition, California's Assembly Bill 32 (AB32), the Global Warming Solutions Act of 2006, went into effect in 2012 and currently allows for the creation of offsets from U.S.-based forest carbon projects. Here we highlight the two most popular protocols/registries in the voluntary markets, as well as California's Compliance Offset Protocol, to provide some context for how a forest carbon project might be developed within the United States. Because the voluntary carbon market is still evolving, we have not included specifics of each entity's methodologies here, but more information can be found on their Web sites.

- **Verified Carbon Standard (VCS)—**The Verified Carbon Standard (2013) is one of many standards available in the decentralized OTC market. The VCS is a third-party project standard that markets itself as providing a "robust quality assurance standard that projects can use to quantify greenhouse gas emissions and issue credits in voluntary markets." The VCS provides both protocol standards and a registry system for generating and tracking carbon offsets. The VCS was developed by the Climate Group, the International Emissions Trading Association, and the World Economic Forum in 2005 and has released several versions of its offset project protocols. The VCS has established methodologies for a variety of agriculture, forestry, and land use-related projects involving improved forest management and avoided conversion. These methodologies, as well as all Clean Development Mechanism (CDM) and Climate Action Reserve (CAR) methodologies (except for CAR's Forest Protocol) may be used to develop and register projects on the VCS registry. Once registered, eligible projects can generate Verified Carbon Units (VCUs) that can be transacted in the OTC marketplace.
- **Climate Action Reserve (CAR)—**The Climate Action Reserve (2013) is a voluntary project standard that evolved from the California Climate Action Registry (CCAR), a California-specific market registry that was created by California law (AB) 32. The Climate Action Reserve project protocols are intended for national use, but are not accepted by all registries (e.g. VCS). CAR also provides its own registry system (the Climate Action Registry Reporting Tool—CARROT) to register Climate Reserve Tonnes (CRTs)—each representative of one metric ton of carbon dioxide equivalent—that are generated by projects. Forest-related projects may include reforestation, improved forest management, and avoided conversion.
- **California's Cap-and-Trade Program: Compliance Offset Protocol—**California's Global Warming Solutions Act of 2006, also known as Assembly Bill 32, required the creation of market mechanisms to reduce greenhouse

gas emissions. California's Air Resources Board (ARB) is responsible for implementing the bill and adopted a cap-and-trade program in 2010 (California Environmental Protection Agency 2013). The program had a soft launch in 2012, and mandatory compliance will be required in 2013. The ARB has specified four offset protocols, of which forestry is one, that can be used to generate compliance offset credits. This protocol allows for reforestation, improved forest management, and avoided conversion forestry projects from throughout the United States.

Public Policies and Regulations

In the past, the U.S. Forest Service has engaged in a variety of pilot carbon credit projects, at least one of which (Midewin Tallgrass Prairie Restoration Project) generated credits on the now-defunct Chicago Climate Exchange. However, leading standards in the voluntary market – including VCS and CAR – may preclude public land participation either explicitly or as a result of their multi-criteria additionality requirements, while requirements related to permanence/risk of reversal that are associated with these standards may conflict with legal issues related to placing encumbrances on carbon flowing from public lands. Also, because public lands in the Midwest and Northeast are typically better stocked than private lands, opportunities for generating additional emissions reductions or sequestration may be less significant.

In general, the state, local, and private forest lands that surround and border National Forests may be better able to engage in voluntary or other carbon markets. An emphasis on multiple uses and overall ecosystem integrity rather than carbon maximization guides planning on National Forest System lands. However, experimental or research areas within National Forests may be used to develop or demonstrate management practices that can yield additional carbon storage, or may be used as benchmark or reference sites to validate measurements, approaches, or models.

There is policy guidance for assessing carbon stocks on public lands. Executive Order 13514 requires periodic reporting of net carbon stock changes on forest land as related to land management techniques. Under the National Environmental Policy Act, supplemental draft guidance for Federal agencies asks whether the impacts on carbon sequestration and greenhouse gas emissions are being considered in land management decisions. The Forest Service Planning Rule of 2012 includes a provision to identify and evaluate existing information relevant to the plan area for a baseline assessment of carbon stocks. The USDA Strategic Plan for 2010-2015 has an objective to lead efforts to mitigate and adapt to climate change. These regulations prompted the Forest Service to develop a climate change scorecard (U.S. Forest Service 2013c) comprised of 10 elements designed to gauge performance in a wide variety of climate change activities, including element 9 to: (1) develop a baseline assessment of C stocks, and (2) assess the influence of disturbance and management activities on C stocks. This scorecard element reflects the fact that both forest management and natural factors can influence CO_2 removal rates or emissions from forests.

DISCUSSION AND CONCLUSIONS

This technical report provides an in-depth example of using currently available monitoring data and estimation methods to assess past and prospective carbon stocks for all lands in a forested region of the Eastern United States. Future analyses may also integrate anticipated effects on forests as a result of climate change to address the potential viability of mitigation options given expected changes in climate, impacts on forest ecosystems, and management responses for adaptation.

Private landowners hold 63 percent of the forest carbon stock in northern Wisconsin, followed by state and local ownership (24 percent), and National Forest ownership (14 percent). Over the last decade, carbon stocks of northern Wisconsin forests have been increasing by about one million metric tons per year, a little less than the previous decade. This reduction compared with the previous decade was likely caused by aging forests growing more slowly and, in other forested areas, continued or increasing use of wood for industrial products, which transfers a portion of carbon that is removed from the ecosystem to the wood product carbon pools. Since 1990, carbon in harvested wood products has been increasing by 0.5 million metric tons per year; thus in total, the net carbon sequestration in northern Wisconsin forests and wood products since 2000 was approximately 1.5 million metric tons per year.

Given the currently healthy status of forests of northern Wisconsin and a broad distribution among age classes, it is likely this level of carbon sequestration along with intensive use for industrial wood products can be sustained unless climate change or natural disturbances increase significantly. In the upper Midwest, harvest and fire have been the principal drivers of forest carbon dynamics over the last century with windstorms, insects, diseases, land use change, and other disturbances impacting natural systems as well. The region's forests and carbon stocks have been sustained despite these agents causing tree damage and mortality to varying degrees. Many of the current stressors that act upon the forests of northern Wisconsin are expected to increase as a result of climate change, which poses a significant threat for sustained ecosystem production in this region.

There is potential to increase stocking on the land by allowing more of the forest area to reach older age classes. However, net ecosystem production declines as forests age, so even though such an increase could be substantial, it would be limited over the long term. Reduced harvest or lengthening of harvest rotations would increase carbon stocks but also cause a substantial loss of carbon being sequestered in wood products or providing bioenergy to substitute for fossil fuels, illustrating the tradeoffs between increased carbon uptake by forests and utilization of wood for wood products or bioenergy. There will most likely continue to be substantial changes in land use causing some loss of forest land, and the ability to change this trajectory under alternative policy scenarios appears to be relatively small.

Private entities have emerging opportunities to change land management practices to increase carbon stocks in forests and wood products, as well as to participate in markets for ecosystem services that include carbon sequestration. Public lands contain large stocks of carbon and function as carbon sinks, though are unlikely to participate in carbon markets or registries. Although specific carbon targets are not driving land management decisions, the effects of land management decisions on carbon stocks are beginning to be estimated and reported.

The estimates in this report rely heavily on data from the Nation's Forest Inventory and Analysis (FIA) program. FIA forms a solid foundation of information, consistently available over time and for all of the United States. We augmented the information from FIA with remote-sensing based analyses and ecosystem models because many of the carbon pools of interest are difficult to observe directly and well-validated models will provide valuable information about future forest conditions under various management, disturbance, and policy scenarios. As models improve and newer data becomes available, this analysis can be easily updated.

This project was a pilot study to assess how to improve the availability of quantitative carbon information and assessment for public and private lands. The methods used here can be adapted for use by other regions or forests to assess carbon stocks and effects of management on future carbon stocks. Methods will improve over time to provide more comprehensive and timely information that will support science-based policy and management decisions.

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This report assesses past and prospective carbon stocks for 4.5 million ha of forest land in northern Wisconsin, including a baseline assessment and analysis of the impacts of disturbance and management on carbon stocks. Carbon density (amount of carbon stock per unit area) averages 237 megagrams (Mg) per ha, with the National Forest lands having slightly higher carbon density than other ownership classes. Over the last decade, carbon stocks of northern Wisconsin forests have been increasing by about one teragram (Tg) per year or 0.22 megagrams per ha per year, with most of the increase in live biomass. Harvest, wind, and fire have been principal drivers of forest carbon dynamics over the last century. For all forest types in northern Wisconsin, there is potential to increase stocking on the land by allowing more of the forested area to reach older age classes or by increasing productivity. Opportunities to increase afforestation and reduce deforestation are limited, but the potential exists for utilizing biomass energy as a substitute for fossil fuels. There are several options for private landowners to participate in carbon markets or greenhouse gas registries and receive some credit for additional actions to reduce emissions or increase sequestration of carbon. The methods used here can be adapted for use by other regions or forests to assess carbon stocks and effects of management on future carbon stocks.

KEY WORDS: Carbon stocks, forest management, climate change, mitigation, inventory, monitoring

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