Terrestrial Carbon Sequestration
Monitoring Networks and Demonstration Sites

Part II, Report to the Minnesota Department of Natural Resources
From the Minnesota Terrestrial Carbon Sequestration Initiative

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Executive Summary

This report covers the final phase of a University of Minnesota study requested by the Minnesota State Legislature (MN Session Laws 2007 Chapter 2, Section 35) to assess the potential capacity for terrestrial carbon sequestration in the state. It focuses on creation of a network of monitoring and demonstration sites to collect information and educate the public about carbon sequestration practices and their impacts. The report builds on a preliminary report submitted to the legislature in early 2008 that concluded that land use and land management changes in Minnesota forests, agricultural areas, wetlands, and grasslands could make modest but important contributions to the state's greenhouse gas reduction efforts. The Minnesota Terrestrial Carbon Sequestration Initiative Task Force, a stakeholder forum overseeing production of the report, developed three recommendations based on these findings: (1) preserve existing large carbon stocks in peatlands and forests; (2) promote land use and management changes most certain to cause carbon sequestration by including them in local, regional, and statewide conservation, renewable energy, and sustainable development programs; and (3) invest in monitoring and demonstration programs in order to build public, practitioner, and investor confidence in terrestrial carbon sequestration as a viable greenhouse gas reduction strategy.

The present report responds to specific legislative requests to

> *Identify a network of benchmark monitoring sites to measure the impact of long-term, large-scale factors, such as changes in climate, carbon dioxide levels, and land use, on the terrestrial carbon sequestration capacity of various land types, to improve understanding of carbon-terrestrial interactions and dynamics*; and

> *Identify long-term demonstration projects to measure the impact of deliberate sequestration practices, including the establishment of biofuel production systems, on forest, agricultural, wetland, and prairie ecosystems*

I. Monitoring Network

The purpose of the monitoring network is to assess changes in the state's net carbon balance related to land management. This requires both an assessment of changes in the areal extent of relevant land use / land management practices and a determination or estimation of the net carbon sequestration rates associated with land use / land management practices specific to Minnesota. Three parameters are typically monitored in such assessments.

- Annual rate of carbon flux between various ecosystems (or land uses) and the atmosphere. USDA Forest Service and US Department of Energy monitor carbon fluxes to improve understanding of net carbon balances of existing ecosystems.
- Area of land converted from one land use to another. Numerous monitoring programs in state and federal agencies assess changes in land use categories (e.g., area of cropland converted to forests and vice versa). The USDA's "Census of Agriculture" and "Forest Inventory" track land use changes in all categories for the entire state of Minnesota;
- Annual net carbon sequestration rate associated with land use conversion, expressed on an areal basis. Assessments may be *longitudinal*, capturing changes over time, and/or *comparative*, to determine sequestration differences between test and control sites.

The most important gaps in knowledge needed to promulgate a credible terrestrial carbon sequestration program in the state are in the third parameter: the sequestration rates of specific land use and management practices. The first priority of the monitoring network should be to address these gaps and produce policy- and management-relevant information within a relatively short (3 to 5 year) timescale. Land use practices found to have the highest potential for increasing sequestration in Minnesota on a per-acre or potential scale-of-adoption basis should be the focus of this effort. These practices - afforestation/reforestation; increased stocking of forested land; conversion of annual crops to perennial grasses; use of winter cover crops in annual cropping systems; and wetland restoration – should be evaluated through a set of empirical studies including biomass harvesting, soil sampling, forest measurements, and micrometeorological flux analysis. Linking a rigorously-designed monitoring system to demonstration projects (described below) is necessary to increase the reliability of practical management tools.

II. Demonstration Projects

The overall purpose of demonstration projects is to assess the feasibility of incorporating key carbon sequestration techniques listed above into existing programs and activities and educating the public about it. Many practices known to increase carbon also have environmental and economic benefits, such as reducing erosion, improving water quality, enhancing wildlife habitat and biodiversity, and others. If such a multiple-benefit approach is a viable strategy for contributing to Minnesota's greenhouse gas reduction efforts, cost efficiency and public support should increase.

The projects are designed to fulfill three objectives: educate land managers on the establishment and maintenance of sequestration techniques; document the carbon results of selected management practices; and assess costs and benefits of integrating sequestration into existing projects. Suggested tasks are:

- establish baseline conditions, document land use management changes, assess changes in carbon sequestration using both published carbon accounting protocols and rigorous monitoring techniques; assess other environmental effects;
- track costs, incentives, and returns on project activities; determine eligibility and requirements of government and private or market incentive program;
- conduct educational outreach to practitioners, the public, and policymakers about carbon sequestration practices and their results.

In addition to site-specific information, demonstration projects provide an opportunity to test institutional aspects of a statewide carbon management program. Complimentary studies could provide refined estimates of potential sequestration contributions to greenhouse gas reduction efforts; rigorous analysis of the economic costs of alternative sequestration strategies; and expanded education and outreach about the importance of protecting and enhancing the state's carbon sinks.

Demonstrations of all sequestration techniques suitable in Minnesota should eventually be undertaken. An initial set of projects considers (1) use (or modifications) of practices known to result in positive sequestration values; (2) eco-regional suitability; (3) appropriateness for large-scale adoption in targeted eco-region; (4) support for other conservation and economic priorities; and (5) partnership opportunities.

Following these criteria, five demonstration projects are identified in different eco-regions of Minnesota. Monitoring network sites will be co-located with these projects.

- *Carbon benefits of integrative silvaculture techniques*: The Manitou River Integrative Silvaculture Project is a collaborative effort in northeast Minnesota to test the ability of various sustainable forest management changes to address climate change, invasive insects, and changing timber markets and demographics. Carbon benefits of techniques to increase resilience, such as increasing forest diversity and increasing the proportion of long-lived tree species will be evaluated, along with applicability and accuracy of forest carbon management tools.
- *Carbon benefits of wetland restorations:* Wetlands are major sinks and potential sources of carbon dioxide. Broad partnerships and major initiatives are underway in northwestern Minnesota to restore prairie potholes for wildlife, biodiversity, flood reduction, and water quality protection. A demonstration project in the Bois de Sioux River watershed will support these efforts by investigating carbon sequestration and other greenhouse gases associated with wetland restoration and the compatibility of carbon management practices with broader goals.
- *Carbon benefits of winter cover crops*: In the Zumbro River region of southeast Minnesota, a study of carbon sequestration resulting from inclusion of winter cover crops in corn-soybean rotations will be added to long-term research on cover crops by a group of farmers, local and state agencies, and UMN researchers. Cover crops promote soil fertility, protect surface waters, and may mitigate the loss of corn stover as biofuel.
- *Carbon benefits of perennial biofuels*: The increased use of biomass in the nation's energy supply is an important driver of land use in agricultural areas of the state. A demonstration project will be established in partnership with Koda Energy to improve understanding of carbon sequestration implications of perennial, grass-based systems harvested for biofuel. The project builds upon an extensive study of perennial biofuel systems in central Minnesota.
- *Carbon benefits of urban forestry and green infrastructure*: Many watershed management authorities and communities are developing "green infrastructure" projects to improve water management, recreation, and biodiversity conservation. This demonstration in the Minnehaha River watershed in the Twin Cities metropolitan area will examine the carbon benefits of urban forestry in watershed management and work with local and state partners on strategies to protect and restore carbon stocks in the watershed.

Introduction

As part of the legislative request (MN Session Laws 2007 Chapter Article 2, Sec. 35), the Board of Regents of the University of Minnesota were asked to "*identify a network of benchmark monitoring sites to measure the impact of long-term, large-scale factors, such as changes in climate, carbon dioxide levels, and land use, on the terrestrial carbon sequestration capacity of various land types, to improve understanding of carbon-terrestrial interactions and dynamics*" and to "*identify long-term demonstration projects to measure the impact of deliberate sequestration practices, including the establishment of biofuel production systems, on forest, agricultural, wetland, and prairie ecosystems*". This report summarizes our findings and recommendations with regard to those tasks.

Purpose / Objectives

The purpose of a monitoring network is to assess changes in the state's net carbon balance related to land management. This requires both an assessment of changes in the areal extent of relevant land use / land management practices and a determination or estimation of the net carbon sequestration rates associated with land use / land management practices specific to Minnesota.

Demonstration projects have three purposes: to educate land managers about the establishment and maintenance of sequestration techniques; to document the carbon results of selected management practices; and to assess costs and benefits of integrating sequestration practices into existing projects. The projects will also test the application and accuracy of management tools designed to assess carbon and other environmental and financial impacts.

This report describes a linked system in which an extensive network of demonstration projects and a small number of monitoring sites can complement and inform one another to produce management- and policy-relevant information on the carbon sequestration impact of land use / land management changes suitable for Minnesota.

Background

In February, 2008, the Minnesota Terrestrial Carbon Sequestration Initiative submitted a report to the Minnesota Department of Natural Resources entitled "*The Potential for Terrestrial Carbon Sequestration in Minnesota*" (Anderson et al., 2008). This document reported the findings of an interdisciplinary research group on the potential of various land use practices to sequester carbon in Minnesota. It analyzed the existing scientific literature to determine potential rates of carbon sequestration related to land use / land practice changes; the potential areas of land existing in broad land use categories; and the role of current state policies and programs on carbon sequestration potentials. Based on this information, analysts also developed several scenarios to illustrate the potential magnitude of terrestrial carbon gains resulting from broad adoption of land management changes associated with (1) biofuel production; and (2) a diversified strategy including afforestation, increased stocking of under-stocked forests, and conversions of cropland to perennial vegetation. These scenarios, though only coarse estimations of what might be possible, resulted in estimates that terrestrial carbon sequestration could reduce net greenhouse gas emissions in the state by approximately 3 – 6 million metric tons annually, a modest but worthwhile contribution to the state's greenhouse gas reduction efforts.

Table 1.0. Estimated carbon sequestration potential for various land use changes in Minnesota. Sequestration rate means and standard deviations are calculated from all studies for a particular land use / management category.

Land Use Change	**Mean Sequestration Rate**		**Level of Certainty**	
	Metric tons CO_2 equivalents $acre^{-1}$ yr^{-1} ± S.D.	Relative Rate	about the mean rate	that carbon sequestration > 0
Annual row crop to short-rotation woody crops	7.0 ± 2.6	High	High	Very High
Annual row crop to forest	5.5 ± 1.8	High	High	Very High
Prairie pothole restoration	4.5 ± 6.9	High	Low	Very High
Annual row crop to perennial grassland	1.6 ± 1.6	Medium	Low	High
Turfgrass to urban woodland	0.9 ± N.A.	Medium	Low	Very High
Enhanced forest stocking	0.8 ± 1.0	Medium	Low	High
Peatland restoration	0.74 ± 0.4	Low	Medium	Very High
Inclusion of cover crops in row crop rotation	0.6 ± 0.3	Low	Medium	High
Annual row crop to pasture / hayland	0.4 ± 0.1	Low	High	High
Conventional to conservation tillage	0.3 ± 0.5	Very Low	Low	Very Low
Low diversity to high diversity grassland	0.1 ± 1.39	Very Low	Low	Very Low

The initial report to the DNR focused on land use / management practices for which empirical research data exists and that were applicable to large areas of Minnesota. Table 6.1 of that report presented the mean (average) carbon sequestration rates for each of the practices investigated plus the minimum and maximum rates obtained from the literature, the number of studies cited, and the standard deviation around the mean. Table 1.0 above is an abbreviated version of Table 6.1 from the previous report.

Of particular interest in Table 1.0 are those practices that have both relatively high carbon sequestration rates and high confidence that those rates are greater than zero. These include afforestation (conversion of annual row crops to forest or to short rotation woody crops), prairie pothole restoration, conversion of annual row crops to perennial grasslands, conversion of turfgrass to urban woodlands, and enhanced forest stocking. These practices were found to have the highest potential, on a per acre basis, to sequester carbon in Minnesota.

The report recognized that many of the most promising carbon sequestration practices for Minnesota have multiple benefits associated with them, such as reducing erosion, improving water quality, enhancing wildlife habitat and biodiversity, and others. Many of these practices are already being implemented as part of state or federal programs aimed at achieving one or more of these other goals. The report recommended that, where appropriate, carbon sequestration techniques and objectives be incorporated into broader conservation, renewable energy, and sustainable development programs.

The report also recommended that the state invest in monitoring and demonstration in order to build public, practitioner, and investor confidence in terrestrial carbon sequestration as a viable greenhouse gas reduction strategy. A major conclusion of the report is that protecting and enhancing the state's carbon stocks are important resource management priorities that need research and education to be implemented successfully. The chapters that follow describe in detail how such programs should be established.

A note on the science – land use nexus

The understanding of terrestrial carbon sequestration is still in its infancy. The carbon sequestration behaviors of relatively simple land use conversions, such as those described in the table above, are fairly well understood, although the rates of carbon sequestration may vary from one region to another and may need to be refined for local conditions. The area of land available for these types of conversions from land uses with low carbon sequestration rates to alternate land uses with higher carbon sequestration potentials is, however, generally limited due to competing land uses. Consequently, the relatively simple land use conversions described above have only a limited potential to sequester carbon and offset Minnesota's total carbon emissions.

Conversely, if existing land management practices on millions of acres of public and private land can successfully be modified to incorporate carbon management objectives, a much larger emission offset could potentially be achieved. Unfortunately, the ecosystem-scale carbon dynamics associated with more complex management systems, such as management of forests for multiple benefits (e.g., timber production, wildlife habitat, water quality, recreational use) are poorly understood due to the spatial complexity of natural ecosystems and an almost complete lack of knowledge regarding the interactions among the numerous physical, biological, and microbial processes that affect the carbon balance of these systems. Under these circumstances, the potential for unforeseen behaviors and unintended consequences exists.

Because of the urgency associated with reducing the state's net carbon emissions, and because state agencies and private landowners already manage lands for multiple goals and objectives, there is a strong desire to add carbon management to the list of existing land management goals. The political will to sequester carbon has moved ahead of our understanding of the net effects of the more subtle management practices that might be readily implemented.

In spite of our lack of a comprehensive understanding of these systems, land managers will need to incorporate carbon management goals into their current multiple benefits management practices. Thus, they will need to modify existing land management practices in ways that, at the current state of the science, appear to have the greatest potential to sequester carbon. At the very least, these practices, when compared to the net carbon balance of the existing land management practices, should not increase net carbon emissions over the project duration. Fortunately, carbon sequestration goals are generally highly compatible with many other land management objectives addressed by current management objectives.

In the sections that follow, monitoring and demonstration of both types of conversions – simple land use changes and more complex changes in management– are proposed.

Section One: Monitoring Network

This chapter provides background information regarding the terrestrial carbon cycle, practices for monitoring carbon sequestration, methods of measurement, and recommendations for an independent monitoring network. Monitoring of practices associated with the demonstration sites is described in Section Two, Part III.

Background

The terrestrial carbon cycle consists of a number of pathways, including photosynthesis, whereby green plants take up carbon dioxide (CO_2) from the atmosphere and incorporate it into their tissues; respiration, where plants release CO_2 back to the atmosphere; incorporation of dead plants and plant remains into the soil as organic matter; and soil respiration, whereby microbial organisms (bacteria and fungi) slowly decompose organic matter, releasing CO_2 back to the atmosphere, thus completing the cycle.

Terrestrial carbon sequestration occurs when the quantity of carbon in terrestrial carbon pools (mainly plant biomass or soil organic matter) increases over time. Increases in the size of the terrestrial carbon pool occur at the expense of the atmospheric CO_2 pool, thus leading to a decrease in the quantity of greenhouse gases in the atmosphere, or at least a decrease in the rate of increase of atmospheric CO_2 concentrations. Different land use practices have different capacities to sequester carbon; some (such as draining of peatlands or wetlands) produce net carbon emissions (negative sequestration). Others, such as forest growth, which captures carbon in aboveground and belowground (roots) biomass, have positive net sequestration values and increase the size of ecosystem carbon pools.

The quantity of carbon sequestered by a land use practice is calculated by multiplying the carbon sequestration rate (expressed as metric tons of carbon [or CO_2 equivalents] sequestered per acre per year) times the area of land (acres) times the number of years that the practice has been in effect. In the case where an area of land is converted from one land use to another, the quantity of carbon sequestered is calculated by multiplying the area of land times the number of years times the difference between the sequestration rates associated with the two land use practices.

I. Types of Monitoring

Monitoring is a term used to describe the repeated measurement or observation of a parameter over time. This might consist of establishing a baseline measurement and then repeating that measurement at one or more intervals, or a more continuous set of observations occurring at much shorter intervals. With respect to terrestrial carbon sequestration, there are three main parameters that are commonly monitored. The first is the area of land that has been converted from one land use to another. The second is the annual net carbon sequestration rate associated with a land use conversion, expressed on an areal basis. The third is the annual rate of carbon flux between various ecosystems and the atmosphere, a measure of the net carbon balance of existing ecosystems. Each of these situations will be addressed separately, starting with monitoring of stable land uses.

A. Stable Land Uses

The monitoring of carbon flux rates occurring between stable land uses and the atmosphere is used as a background measure of ecosystem response. It is a critical part of any understanding of the overall net carbon balance, but one that is not counted in carbon emission offsets since it represents "business as usual" and thus is not an improvement over the current condition. Two federally-funded programs monitor the carbon dynamics of stable land uses. These are the US Department of Energy supported AmeriFlux program, a part of the global FluxNet program, and the USDA Forest Service's Forest Inventory Analysis (FIA) program.

The AmeriFlux program supports a series of micrometeorological flux towers (currently about 85 are active, 5 are located in Minnesota) generally situated over a variety of stable land uses, including forests, tundra, peatlands, grasslands, and agricultural sites. These sites are outfitted with complex instrumentation that measures whole ecosystem CO_2 fluxes and can be used to provide net carbon fluxes for specific stable land uses. The data from these sites is used to help understand the global carbon cycle. AmeriFlux data are readily available and can be used to estimate the net carbon sequestration rates associated with similar land uses common in Minnesota.

Ameriflux sites in Minnesota include: the KCMP tall tower at Rosemount, which measures fluxes from a mosaic of croplands, industry, and the southern Twin Cities Metro region (depending on wind direction); the KUOM tall tower on the St Paul Campus of the University, which measures fluxes from the Twin Cities urban region; and three short (2 meter) towers measuring fluxes from agricultural fields at the UMore Park Research and Outreach Center at Rosemount under corn-soybean rotations subjected to specific treatments (conventional tillage, no-till, and a ryegrass winter cover crop).

The USDA Forest Service has been conducting forest inventory using the FIA protocols since 1930. The FIA protocols are based on a combination of remote sensing techniques to determine aerial extent and density of the forests, and a set of detailed forest mensuration, or measurement, techniques to measure aboveground biomass. The FIA inventory is applied to all forested lands in the U.S. every five years, with 2007 being the most recent survey year. Summary data are widely available, but information about the location and status of individual plots is not available to the general public due to privacy concerns.

B. Land Use Change

Determination of the net carbon sequestration (or carbon offsets) associated with a change in land use requires knowledge of the area of land that has been converted from one land use to another and the net carbon sequestration rates for both the previous and the new land use practice. Although these two types of monitoring are complementary in use, they are quite different in practice, and thus will be addressed separately.

Monitoring the areal extent of land uses, and hence land use change, can have multiple goals, including prediction of harvest yields, extent of wildlife habitat, and general land use trends for specific regions of the country. Numerous land use monitoring programs are in existence in various state and federal agencies, most of which have been established to monitor one or two specific land use types. Development of a comprehensive land use monitoring system from these detailed individual programs is difficult due to differences in scale, different measurement periods or times, and differences in land use definitions in use by these programs. This last issue can be particularly problematical. For example, if a wetland supports tree growth, is it classified as a forest or as a wetland? If you combine the "forest" land use data collected in one survey with the "wetland" land use data collected by another, this parcel of land (and all similar ones) might be counted twice (as "forest" by one group and "wetland" by another) or perhaps not at all.

Consequently, it is best to use a unified system performed by a single organization. The advantages are that each land type is classified in only one category; measurements are typically performed within the same time frame and at the same scale; the results are already compiled; and the results are comparable to other areas or regions assessed by the same organization. For the overall purpose of determining land use changes for the entire state of Minnesota, the "Census of Agriculture" compiled by the USDA Agricultural Economics Service provides many of the qualities that are desired. It is a single classification system applied uniformly to the entire US, thus providing inter-state comparability. It is taken every 5 years (the last Census was taken in 2007). And it provides county-by-county details for nearly all significant land use categories of interest (acreages of important row crops, pasture and haylands, fallow or idle lands, forest land, and numerous other categories) to a comprehensive carbon sequestration program.

For forested lands, additional detail regarding areal extent or changes in forest species composition, stocking rates, age distribution, and numerous other aspects is collected every five years by the USDA Forest Inventory. Like the Census of Agriculture, the Forest Inventory has a wealth of data on current land use and land use changes, is collected in a uniform manner across the U.S., has a highly standardized and uniform data set, and is compiled and published every five years concurrently with the Census of Agriculture.

C. Carbon sequestration rates

Carbon sequestration rates are generally determined by either *longitudinal* studies or by *comparative* studies. Longitudinal studies take two or more measurements of the carbon content of an ecosystem component, or pool (such as forest biomass), separated by an interval of time sufficient to allow changes in the carbon content to be observed. For observations of the effect of land use change on the carbon content in a pool, a baseline measurement is usually taken prior to initiation of the land use change and then again at a later date(s). The difference between these two measurements can be used to calculate the carbon sequestration rates. Alternatively, if a series of existing sites that have undergone this same land use change at different dates in the past can be found, it is possible to measure their carbon pools and determine the carbon sequestration rate associated with a specific land use change from this "chronosequence" of sites.

Comparative measurements involve a "treatment" site, whose management or land use is changed, and a "control" site, which is still maintained under the same land use management / practice it was subjected to prior to the initiation of land use management / change on the treated site. Carbon contents of the ecosystem pools of the control and treatment sites are then compared at some time following initiation of land use / management change to determine the effects of the treatment. As above, pre-existing sites may be used to determine the carbon sequestration rates if sufficient information exists about them.

II. Monitoring Network Criteria and Design

To be useful for policy analyses, a monitoring program needs to rigorously determine the carbon sequestration impact of specific land use / management practices within a relatively short (3 to 5 year) timescale. Additional measurements may be desirable to provide baseline carbon quantities for longer-term monitoring.

Overall objectives:

- Produce statistically significant measures of carbon sequestration rates for specific land use / management practices;
- Develop a rigorous analytical and statistical design that will stand up to vigorous peer review and critical analyses; and
- Provide sequestration rates that can be extrapolated across the region to estimate carbon sequestration resulting from land use / management changes at sites not monitored.

Timeframe:

- Achieve measurable results of carbon sequestration rates within a relatively short (~ 5 year) period that roughly coincides with areal measurements of land use change;
- Sampling schemes should allow for future follow-up sampling to determine carbon sequestration rates over a longer (20 - 100 year) timeframe. This may require development of an independent sampling / measurement scheme for some monitoring methods (particularly micrometeorological flux methods); and
- Where methods (e.g., micrometeorological flux methods) are capable of determining carbon sequestration rates or differences between two or more land use / management practices on an annual basis, monitoring should continue for 3 to 5 years in order to observe or account for the effects of inter-annual climate variability.

Monitoring site locations:

- Located on public lands so that ownership and/or control of the lands does not change during the monitoring period;
- Should be geo-referenced so that exact sampling locations can be re-visited in the future;
- Should be co-located with demonstration sites where feasible; and
- Site treatments should match the criteria for the specific land use / management strategy being studied.

Methods

- Where feasible, standard methods should be used for sampling and measurement to allow for greater comparability of the results of these monitoring studies with those obtained from other studies.
- Sampling schemes should be designed to assure that statistically significant results can be obtained within the timeframe of interest, typically within 5 years. This may require preliminary analyses of the variability of carbon in pools of interest followed by statistical analyses to determine sample numbers required to achieve the desired results.
- Sampling methods should be sufficiently documented so that they may be replicated in the future by individuals unfamiliar with the study methods.

III. Carbon sequestration monitoring methods

Various methods have been developed to measure the carbon content of specific ecosystem components. A brief description of some of those methods and their applicability follows. Additional information is provided in Appendix 1.

A. Biomass Harvesting

For agricultural and biofuel crops, a considerable quantity of carbon is stored in the aboveground biomass (grain, hay, silage, biofuels) that may be harvested and removed from the site. Determination of the carbon content of biomass is accomplished by direct measurement (usually weight) of the harvested material followed by corrections for moisture content and carbon proportion of total dry weight. The post-harvest fate of the material then determines the ultimate quantity of carbon sequestered (or offset in the case of biofuels) over time. Biomass removal may, however, also affect carbon sequestration in other ecosystem components, notably the soil organic matter fraction, by reducing carbon inputs to the system; thus these measurements are important for determination of total ecosystem carbon budgets and carbon dynamics.

B. Forest Mensuration

Forest biometricians have developed measurement and statistical methods to accurately determine the total quantity of biomass in various forest ecosystem components, such as standing timber, woody debris, understory vegetation, and the forest floor. Additional relationships exist between aboveground biomass of trees and their belowground biomass that allow for reasonably accurate estimation of root mass and carbon content. These are (mainly) non-destructive techniques that can generally detect changes in forest biomass (and C) within a 5 or so year time increment.

Three forest vegetation strata are generally measured: trees (including saplings); tall shrubs; and low shrubs and herbs (including ferns, grasses, and forbs). In addition, carbon estimation also includes sampling for down woody materials, including coarse and fine woody debris. In forests, trees dominate vascular aboveground biomass. In Minnesota, biomass of trees and saplings, at around 100 metric tons per hectare (40 metric tons acre^{-1}), is one to two orders of magnitude higher than that of any other vegetative strata, and generally constitutes about 95% of living biomass. The tall shrub stratum is approximately 2 metric tons per hectare (0.8 metric tons acre^{-1}), while low shrubs generally contribute about 0.1 metric tons per hectare (0.04 metric tons acre^{-1}). Finally, non-woody forbs, ferns, and grasses generally contribute about 0.5 metric tons per hectare (0.2 metric tons acre^{-1}), which varies considerably among different forest types. The estimated biomass of woody debris is more variable, ranging from 10 to 40 metric tons per hectare (4 to 16 metric tons acre^{-1}) for forests in eastern and continental areas of North America.

Appendix B provides more detail about the FIA sampling protocols and also describes criteria for a proposed sampling scheme for monitoring carbon sequestration in forested demonstrations or plots, based largely on the USDA Forest Service's Forest Inventory Analysis (FIA) protocols. The FIA protocols are used across the US and have been intensively studied to determine their accuracy, precision, and statistical variability.

C. Soil Sampling

Soil organic carbon can be measured by techniques that involve the collection of soil samples by coring or careful excavation, determination of their carbon content on a volumetric or weight basis, and extrapolation across the landscape using either conventional (random) or geospatial statistical methods. Determination of changes in soil carbon by soil sampling is difficult, however, due to:

- the relatively large quantities of carbon in soils (soils often contain a few to a few tens of kilograms of carbon per square meter in the uppermost 1 meter of soil);
- the high variability associated with soil organic carbon quantities (standard deviations in agricultural soils typically range from ±10% to ±25% of the mean; variability can be much higher in forested landscapes);
- spatial variability in carbon contents and other soil characteristics associated with changes in landscape position;
- the potential for disturbance, such as erosion or deposition, which is not easily observed or measured, but can strongly bias longitudinal or comparative soil carbon measurements;
- the comparatively small annual changes in soil organic carbon associated with most soil carbon sequestration processes (usually 20 to 100 grams carbon per square meter).

Problems associated with soil carbon variability can theoretically be overcome by extremely intensive sampling. Soils with relatively low (1 to 2%) organic carbon concentrations and relatively low variability (standard deviations between 10 and 20%) may require 10 to 25 samples at each sampling interval in order to detect a 20% change in soil carbon concentrations, the equivalent of 10 to 25 years of carbon sequestration at a rate of 50 g carbon m^{-2} yr^{-1}. Higher sample numbers are required for soils with higher organic carbon concentrations and/or higher variability or to detect smaller relative changes in organic carbon concentrations, greatly adding to the expense of sampling and analysis. Thus, routine soil sampling is poorly suited to determine short-term (1 to 10 year) changes in soil carbon in most ecosystems. Soil sampling does, however, play a useful role in establishing baselines for long-term (50 to 100 year) studies of carbon dynamics.

Appendix 1 provides details on soil sampling protocols and methods, along with their strengths and weaknesses, and some estimates of the numbers of samples required to determine changes in soil organic carbon contents.

D. Micrometeorological Flux Methods

Micrometeorological flux methods directly measure the flux of carbon between the atmosphere and the earth's surface. These methods are highly technical and relatively expensive to implement and operate. Because they directly measure carbon fluxes, they measure the total change in ecosystem carbon without regard to which specific ecosystem components are affected. These methods can be used to provide excellent relative comparisons of carbon fluxes between two or more different land uses or land management practices within a single year's timeframe. Problems associated with these techniques include data gaps produced during precipitation events and calm (windless) periods, and inter-annual variability due mainly to inter-annual variations in climate. Consequently, they are less accurate at measuring absolute fluxes over long periods of time in a longitudinal study, but are well suited for determination of comparative flux differences between land use practices on an annual basis.

E. Modeling

A number of models have been developed (e.g., the Century model) that estimate or predict carbon dynamics and carbon sequestration in a number of ecosystem components. They have commonly been used to predict soil carbon sequestration, particularly in agricultural settings. However, questions have recently arisen about the accuracy of some of these models, particularly with respect to high values predicted for no-till and conservation tillage soil management, values that are largely unsupported by recent direct measurements using micrometeorological flux methods or intensive soil sampling campaigns. Because models are "derivative" methods, that is, they are based on estimated relationships measured or determined in other studies, and not on actual measurements of the study site, they are not considered suitable for a true monitoring network.

IV. Monitoring Land Use / Management Practices of Interest

In the initial report to DNR (Anderson et al., 2008), five specific land use / management practices were considered to have sufficient potential to warrant their inclusion in carbon sequestration efforts in Minnesota. These land use / management practices are known to sequester relatively high quantities of carbon per year, have a high degree of certainty with respect to measured sequestration rates, and have a high likelihood of implementation on large tracts of land in Minnesota. Although none of these practices would be applicable across the entire state, each has the potential to be implemented on thousands to millions of acres, thus providing a high potential contribution to impact Minnesota's carbon budget and reduce net carbon emissions. The five practices are listed below, followed by descriptions of monitoring considerations:

- afforestation and reforestation, including short-rotation woody crops;
- conversion of annual to perennial grasslands / prairies
- the inclusion of cover crops into a corn-soybean rotation;
- enhanced forest stocking; and
- prairie pothole restoration.

A. Afforestation / reforestation

A considerable body of information exists regarding the rates of forest growth and biomass accumulation in afforested / reforested sites from across the country and around the world. Data specific to Minnesota exist in the FIA database, in private hands, in University studies, and in DNR records. It would be a fairly simple task to mine these data to determine applicable carbon sequestration rates for the various forest types in Minnesota. If additional information is needed for specific forest types, such as short rotation plantations, biomass stocks on existing forested sites could be measured as part of a chronosequence study utilizing FIA-type protocols on stands of known age, determined from planting records or tree cores. This approach could be especially desirable for short-rotation woody crops, which have been planted on far fewer acres than more common forest types. We also know far less about their growth rates in Minnesota. Biomass measurements on a series of sites of known age could provide a wealth of data for determination of actual growth rates and potential biofuel production or carbon sequestration rates of short-rotation woody crops. The interpretation of chronosequence studies is greatly aided by good records noting planting densities, thinning procedures, damage by insects or other pests, etc.

B. Perennial grasslands and prairies for biofuel production
Carbon sequestration in grasslands and prairies is mainly associated with increases in soil carbon storage. The quantity of carbon stored in standing biomass is negligible in comparison and reaches its maximum value in just a few years. This is particularly true when all or nearly all of the aboveground biomass is harvested for biofuel. By contrast, soil carbon may increase for hundreds or possibly thousands of years. Consequently, monitoring efforts on grassland systems are focused on determining changes in soil C.

Harvesting of biomass for biofuel or other purposes alters the carbon balance of grasslands by removing a significant portion of the carbon inputs to the system. The effect of this modification of a well-studied land use practice is unknown, and thus warrants monitoring. Because of the strong west-to-east climatic gradient in Minnesota with respect to precipitation and temperature (see Figs. 1 and 2), it would be useful to establish both an eastern and a western site to monitor carbon sequestration associated with grassland / prairie biofuel production. Overall changes in soil carbon sequestration may be quite variable across this gradient; thus it is important to assess those changes.

A combination of micrometeorological flux methods and biomass harvest measurements provide the best potential to measure changes in soil carbon over a relatively short (less than 10 years) time frame. Micrometeorological flux methods work best when comparing a treatment site with an untreated, or control site. The micrometeorological flux method measures total CO_2 exchange between the atmosphere and the land surface and thus can be used to determine the total amount of CO_2 (and carbon) that is sequestered or, conversely released, by the plants and soil. Measurements of biomass harvest provide accurate measures of the total carbon contained in aboveground biomass. Subtracting the biomass carbon from the total carbon accrual of the land surface provides an accurate measurement of the change in soil carbon storage and hence, the carbon sequestration rate.

C. Cover crops in corn-soybean rotations
Cover cropping is of interest from a carbon sequestration perspective because it has both a direct, albeit small, carbon sequestration benefit, and a potentially larger benefit in production of biofuel. Cover crops add additional biomass to soils and thus increase carbon inputs to the system; however, much of the added carbon is released back to the atmosphere over an annual cycle by microbial degradation and respiration of the added biomass. Cover crops also protect soils from erosion, as they provide effective soil cover during the early spring before corn or soybean canopy closure and in the fall after harvest. Soils may also be protected from erosion in the fall by the conservation practice of leaving corn or soybean residue at the soil surface, where it protects soils from raindrop impact and subsequent erosion.

Because of the high demand for biofuel, demand is emerging for corn stover as a potential biofuel, particularly for use in ethanol plants. This ready source of biomass simply needs to be harvested and transported to the plant; no additional acres need be planted. However, removal of most of the stover would also remove residue from the soil, thus decreasing carbon inputs to the soil which might lead to long-term losses in soil organic matter and soil C, and also greatly increasing the potential for soil erosion. Cover crops may play a valuable role in both protecting soils from erosion and maintaining soil carbon where stover is completely or partially removed for biofuel use. The use of biofuel in the ethanol process would also help reduce fossil fuel use, thus reducing our total carbon emissions.

A combination of micrometeorological flux methods and biomass harvest measurements will provide the best potential to measure changes in soil carbon in these agricultural settings over a relatively short timeframe. Both treatment (sites including cover crops in the corn-soybean rotation) and control (excluding cover crops) sites will need to be established and monitored. Similar research is already being conducted by USDA-ARS and University of Minnesota researchers at the UMORE Park Research and Outreach Center at Rosemount, MN, to determine the carbon sequestration inputs of cover crops to a corn-soybean rotation. An additional site might be required to determine the net effect when stover is removed. A larger project on the inclusion of cover crops is being conducted by the MN Department of Agriculture in the Zumbro River watershed. USDA-ARS and U of M faculty are also working with this particular project. This site is included in the demonstration projects described below.

D. Enhanced forest stocking

Monitoring of enhanced forest stocking is accomplished by forest mensuration methods. To determine the effect of enhanced stocking on carbon sequestration requires comparative methods wherein the management of one set of sites (control sites) is not changed and, in the other set of sites, the stocking rates are enhanced.

Implementation of a monitoring program for enhanced forest stocking requires linkage with an existing demonstration or monitoring project. There are no plans to implement a monitoring project for enhanced forest stocking in the first round of demonstration projects.

E. Prairie pothole restoration

Limited information exists regarding the rates of carbon sequestration in restored prairie potholes, due in large part to the more limited areal extent of these wetlands as compared to forests. Euliss et al. (2006) determined a rate of 305 g carbon m^{-2} yr^{-1} (10.0 metric tons CO_2 equivalent per acre per year) for restored prairie pothole wetlands that are nearly continuously saturated in the Upper Midwest. Unpublished data by Lennon (2008) for carbon sequestration in restored prairie pothole wetlands in Renville county provides a rate on the order of 195 g carbon m^{-2} yr^{-1} (6.4 metric tons CO_2 equivalent per acre per year) for the wettest portion of wetlands experiencing seasonal inundation and only partial year saturation.

Section Two: Terrestrial Carbon Management Demonstration Projects

This chapter identifies five proposed demonstration projects and proposes a framework for both collecting information and educating the public about the use of carbon sequestration practices in different landscapes, about their ability to increase carbon sequestration, and about the feasibility of different implementation strategies. Following recommendations of the Minnesota Terrestrial Carbon Sequestration Initiative Task Force, these are not stand-alone projects, but are demonstrations of how carbon management could be integrated into conservation and renewable energy programs. In addition to increasing cost-efficiency, such a strategy is designed to leverage a range of benefits and an existing infrastructure of programs and partnerships. Although demonstration projects are focused on producing practical information for land managers and policymakers, they should be rigorously monitored in order to verify estimates of carbon sequestration and evaluate the reliability of management tools.

I. Purposes of Demonstration Projects

The demonstration projects identified in this report are designed to serve illustrative, evaluation, and feasibility testing purposes.

A. Illustration
At their most basic educational level, demonstrations should show practitioners, including public and private land managers and consultants, how sequestration practices are properly applied or modified to increase carbon benefits. Demonstrations are successful and widely-used tools for educating the public about establishment and maintenance requirements of innovative land management practices and the factors contributing to success and failure. Some sequestration practices are relatively well known, but others – such as cover crops and biofuels systems - are not. Practical information about how practices should be applied, particularly in context of broader programs and activities, will be disseminated through field days, fact sheets, and other venues.

B. Technical evaluation
A second, more substantive purpose of demonstration projects is to evaluate the effectiveness of management or land use changes to sequester carbon. Quantifying the results of deliberate sequestration activities is difficult, given the heterogeneity and variability of ecosystems and, at present, considerable uncertainty exists about the reliability of practical methods of estimating and documenting changes in sequestration. A key consideration in demonstrating carbon sequestration, particularly in relation to carbon offset markets, is the credibility and cost-effective of tools used to measure and verify changes in carbon stocks. Demonstration projects should be used to test management tools and protocols and should be linked to more rigorous monitoring to confirm their accuracy.

C. Feasibility testing
In addition to strictly technical outcomes, demonstration projects can be used to test the feasibility of widespread implementation of sequestration practices and their integration into existing programs or systems. In this sense, demonstrations function as case studies in how

particular sequestration practices can be employed in different programs, how much they cost, and other implementation issues described below. Answers to these questions will help identify strategies most likely to be adopted successfully.

- *Costs and returns.* Document and evaluate costs and revenues associated with carbon management activities. Expenditures include project planning; land use costs; initial establishment and annual maintenance; insurance; and measurement, monitoring and verification and, if applicable, registration and reporting. Public expenditures may include long-term or permanent easements to protect carbon stocks. Revenues may come from one or more public or private incentive programs (cost-share, grants, loans, offset credits); additional payments for harvested production (biofuel or animal feedstock), timber, and recreation; and tax benefits.

- *Positive and negative environmental effects.* Many management practices increase carbon sequestration by increasing perennial vegetation. Environmental co-benefits commonly associated with the establishment of perennial vegetation may include: reductions in erosion and/or sediment loading to surface waters; reduced aquatic nutrient loading; and possibly reduced use of herbicides, pesticides, fossil fuel use, and reductions in other greenhouse gas emissions. Many of these practices are known to improve groundwater recharge, enhance wildlife and fish habitat and biodiversity, recreational values, and flood retention. Urban forestry contributes to greater energy efficiency and aesthetic values. If poorly designed or sited, on the other hand, some carbon sequestration projects could have negative effects on biodiversity and other values. Documentation of project objectives and the primary non-carbon effects (positive and negative) of project activities should be conducted by project partners with appropriate expertise.

- *Institutional considerations.* Policy analysis presented in the preliminary report identified eighteen state programs concerned with forest health and productivity, water quality, agricultural sustainability, wildlife and biodiversity conservation that could help finance carbon sequestration efforts. Attention should be given to how improved carbon management can be integrated into these other land management programs, whether trade-offs exist, and what modifications could be recommended. In addition to programs, demonstrations should identify potential institutional partners in the non-profit, for-profit, government, and educational sectors that could help build ownership, sponsorship, and some consistency for a statewide effort. Specific to carbon offset markets, an assessment of project eligibility, requirements, and anticipated returns should be conducted of applicable carbon registries and programs.

- *Carbon accounting and reporting for offset programs.* Turning carbon stored in terrestrial ecosystems into carbon offsets – the financial instruments used in cap-and-trade programs - involves a complex set of calculations aimed at quantifying the net greenhouse gas reductions resulting from specific activities. While requirements vary between programs, most high-quality offsets must be shown to be:

  Real, meaning the effects of a project must be comprehensively accounted for, including any increases in emissions that occur elsewhere because of the project (such as increased timber harvest elsewhere because of restrictions at a project site);

Additional, or “in addition to” removals that would have occurred under business-as-usual projections;
Verifiable, meaning that effects can be measured with reasonable precision and certainty;
Permanent, meaning that projects will result in permanent reduction, avoidance, or removal of greenhouse gases or be backed by guarantees and safeguards to minimize and replace non-permanent removals; and
Enforceable, consistent with regulations and administrative rules.

- *Risk assessment.* A central issue with carbon sequestration is its potential for reversibility. To address this problem, carbon offset programs may require a buffer reserve of non-tradable carbon credits to cover unforeseen losses in carbon stocks. The number of buffer credits that a given project must deposit into a reserve account is based on an assessment of the project’s potential for future carbon losses. Project sponsors conduct an initial risk assessment to determine the transient and permanent potential losses and to calculate an appropriate reserve. Periodic verification is used to determine if a project is performing or underperforming (and identify common characteristics of underperforming projects) and to adjust size of reserves accordingly.

II. Framework for Demonstration Projects

Ideally, demonstrations of each appropriate sequestration practice should be conducted in different eco-regions of the state. This would make it possible for landowners and managers to have ready access to demonstrations and fact sheets on all appropriate practices in their region. Although it is impossible to do immediately, such a program could be constructed over time to provide research and education opportunities for a variety of audiences.

A subcommittee of the Minnesota Terrestrial Carbon Sequestration Initiative Task Force developed a framework for demonstrating carbon management techniques statewide and plans for an initial set of proposed projects. Objectives associated with the demonstration sites are to produce practical information for public and private lands managers, consultants, and policymakers concerning:

- the establishment, management, and maintenance of carbon sequestration practices through land use, cover, and management changes;
- the reliability of management tools for estimating carbon sequestration rates, evaluating costs and returns, and assessing risk;
- incentives from government and private sources and their requirements, including for registering, accounting, and verifying carbon offsets.

A. Criteria for project selection

A number of scientific, socio-economic, and environmental factors will determine the relative success of different carbon management strategies to contribute to greenhouse gas reduction efforts. To prioritize those practices with the highest probability of success, several factors were considered in the selection of demonstration sites.

First, the demonstration site makes use of practices believed to have positive sequestration value. Five sequestration practices have been highlighted as having relatively high levels of scientific certainty in their ability to increase carbon sequestration. These practices – afforestation and reforestation; establishment of perennial grasslands; cover crops; enhanced forest stocking; and wetland restoration – are also compatible with major conservation, renewable energy, and sustainable development programs in the state. Unfortunately, scientific evidence does not currently exist for how well these practices will sequester carbon when they are applied or modified in multi-purpose activities, e.g., the effects on carbon balance of harvesting biomass for biofuel, Demonstration projects could help increase understanding and confidence in the carbon sequestration values of these applications.

Second, demonstration site selection should take an eco-region approach. Optimal terrestrial sequestration strategies vary with the diverse biological, physical, and land use characteristics of Minnesota's major geographic regions. Abiotic and biotic conditions (climate, topographic relief, soils, and plants) in each region determine which sequestration practices could be effectively applied. The Minnesota DNR's Ecological Classification System delineations at the Province scale, based on geology and vegetation, can be slightly modified to serve as a basic template for targeting sets of sequestration strategies most likely to fit the agro-ecological characteristics of a region. Within these major provinces, watershed, land use and cover, ownership patterns, public objectives, and other factors must be considered.

Third, the practice is appropriate for large-scale application in a targeted eco-region. To contribute significant reductions to the state's greenhouse gas inventory, carbon sequestration or management strategies would need to be improved across very large acreages. Success will depend on identifying practices that can be scaled up without compromising economic and environmental resources and, ideally, could support adaptation to the negative impacts of climate change. Uses of practices that are either controversial or too expensive for broad deployment should have a lower priority. In early 2008, the Minnesota Climate Change Advisory Group reported to the Minnesota Legislature on sequestration strategies likely to have broad social support and estimated the scale at which they could be deployed in coming decades.

Fourth, a practice supports other conservation and economic priorities. A related consideration builds upon a key recommendation of the Task Force to increase terrestrial carbon sequestration in the near term by incorporating it into existing state, federal, and private land use / management programs. Among the numerous avenues for complementary action are major economic and conservation programs, including biofuel production, urban forestry and greenways, water quality improvement, flood protection, sustainable forestry, and fish and wildlife protection and restoration. Assessing their positive or negative effects on greenhouse gas sequestration or emissions provides highly relevant information for policymakers. In addition to existing programs, the newly released *Minnesota Statewide Conservation and Preservation Plan* identifies climate as one of the drivers of change in Minnesota's natural resources and recommends including climate resilience and carbon mitigation in comprehensive land management and conservation strategies for the state's natural resources.

Fifth, a practice provides opportunity to partner with regional groups to implement long-term projects and maximize education and outreach opportunities while minimizing expense. Partnering provides expertise, communication channels, and financial and public support.

The table in Appendix A attempts to synthesize these considerations. It identifies opportunities for implementing multiple-benefit carbon management projects. Integrating deliberate sequestration practices into these efforts may be the most resource-efficient approach for reducing net greenhouse gases by terrestrial ecosystems. Using a multiple objective approach may not maximize carbon sequestration on a per-acre basis and it may increase uncertainty about sequestration rates, but it may prove more acceptable for large-scale adoption.

B. Project plans

The primary objectives are to educate landowners and managers how to conduct carbon sequestration techniques and assess carbon values, economics, and related environmental changes. Demonstrations are co-located with a variety of conservation, renewable energy, and sustainable development programs.

- *Establish baseline conditions and document design and operation of project.* Document boundaries, baseline conditions, and land use history at project site, including estimates of relevant carbon pools (aboveground biomass, belowground root systems, soils). Benchmarks can be based on default tables, estimates in published scientific literature including this report, or direct measurements at the project site. Document how project changes land use, land cover, or land management.
- *Measure carbon sequestration rates and compare to accounting protocols.* Carbon sequestration rates will be measured using best monitoring practices for each land use practice demonstration. These rates will be compared to estimates produced by the demonstration project partners using carbon accounting methodologies (which specify requirements for measuring, monitoring, and verifying carbon stocks and changes over time) to assess baseline and changes in carbon stocks. The results of these two measures of carbon sequestration rates will be compared.
- *Track costs, incentives, and returns of project activities.* Analyze costs of planning, establishing, and maintaining project; transactional costs; and potential income or support payments for project benefits. Carbon offset markets entail high transactional costs to cover periodic measurement, monitoring, and verification of carbon stocks.
- *Assess primary and secondary benefits*. Project sponsors or partners will assess primary purposes (flood protection, water quality, etc) and how carbon sequestration objectives can contribute to or detract from primary benefits.
- *Determine eligibility and requirements of government and private or market incentive programs. Test applicable management and accounting protocols.* Numerous programs exist that could help finance land use changes and practices to protect or increase sequestration. Which incentives are used depends on project type, landowner goals, and requirements of specific programs. Project sponsors will evaluate relevant incentive programs and test application of required protocols and management tools. Carbon offset protocols, in particular, require analysis of a number of issues related to the quantification, permanence and verification of carbon benefits.

- *Conduct educational outreach to target audiences.* Collaborate with project sponsor and partnership groups, government agencies, ad Minnesota Extension research facilities to educate practitioners, the public, and policymakers about the practices and results of carbon sequestration practices.

C. Statewide Implementation Issues

Site-specific demonstrations will not answer some important questions about the implementation of statewide carbon sequestration programs. Policymakers, in particular, will need a better understanding of the costs and returns of such a program.

- *Evaluate public-private implementation strategies.* Identify roles and models for a coordinated network of participating groups to support sequestration efforts. Including terrestrial sequestration as a major contributor to greenhouse gas reduction will require significant efforts in education, project implementation, monitoring, and financial investments. A broadly-defined multiple benefit approach to carbon sequestration could draw upon many private and government groups, including conservation organizations, land management agencies, schools, research facilities, landowner organizations, businesses, and communities.
- *Refine estimations of sequestration contributions to greenhouse gas reduction.* Develop estimations of net CO_2 emissions statewide based on data on current and potential acreages in different land use / cover categories and the net CO_2 effect of conversions. Scenarios in the first phase report describe how different magnitudes of terrestrial carbon gains (or losses) might be accomplished. These scenarios were for illustrative purposes only and were not based on extensive feasibility analyses. Some of this information may be available through the Ameriflux monitoring program.
- *Conduct rigorous analysis of economic costs of alternative sequestration strategies.* Analysis would study the public and private costs of selected sequestration options to achieve different levels of sequestration. The analysis would update and refine an earlier study of sequestration supply curves at different levels of credit payments (Polasky and Liu, 2006). It would produce more accurate estimates of what it will cost to capture significant GHG reductions through large-scale sequestration programs.
- *Conduct statewide outreach and education on terrestrial carbon sequestration.* Provide forum for bringing scientific, government, business, conservation, and other interests to exchange information and perspectives.

III. Demonstration Projects, Initial sites

Project Title: Manitou River Integrative Silvaculture Project

Project Sponsor: Minnesota Department of Natural Resources
Partners: MN Forest Resource Council, The Nature Conservancy, Lake County, Wolf Ridge Environmental Learning Center, U. S. Forest Service

Project background: The Manitou River project aims to restore long-lived conifers, increase habitat and forest product diversity, and increase landscape collaboration on a 1,000-acre, cross-ownership site near Finland, Minnesota. The site is located in the Manitou landscape, a 100,000-acre area of northern hardwood forests, mixed and boreal forests, lakes, streams, and wetlands under a variety of ownerships. The project will use several different silvacultural techniques hypothesized to retain and sequester more carbon than the most commonly used practices (e.g., retaining more legacy trees and patches at times of harvest, using longer rotations, encouraging longer-lived species). The project is part of the Manitou Collaborative, an eight-year partnership of public and private landowners in the area engaged in developing mutually agreeable management strategies. The project also links with a set of adaptive forest management projects conducted by DNR to improve sustainable forest management in the face of climate change, invasive species, changing demographics, and economy.

Carbon demonstration plan:

(1) Establish baseline conditions and document design and operation of project. Document boundaries, baseline conditions, and land use history at project site. Document how project changes land cover and management.

(**2) Assess changes in carbon sequestration and co-benefits.** Conduct inventory-based estimates of carbon stocks in project area, using aerial surveys and field sampling. Monitor selected primary and secondary effects. Identify and test use of indicators of desirable/undesirable effects.

(3) Determine eligibility and requirements of carbon offset and other federal and state incentive programs. Test applicable management and accounting protocols. Evaluate applicability of public and private incentive programs. Conduct appropriate carbon accounting protocols to document carbon stock changes and other benefits associated with changes in forest cover. Analysis will include risk assessment of permanence and leakage, which may be used as a performance standard for similar projects on public land. Develop monitoring and reporting plan.

(4) Track costs and returns. Document time and money required to conduct project and verification requirements. Document income streams from timber harvest and other sources.

(5) Education and outreach. Hold scientific and public education meetings to advise project and produce information on forest carbon sequestration, methods of accounting, and other topics. Post outreach materials and technical reports on the Manitou Collaborative website.

Carbon sequestration monitoring plan:

The Manitou River project represents a case where land managers are modifying current silvacultural practices in ways that are predicted to enhance net carbon accrual in forested landscapes. Replacement of short-lived species (mainly aspen and white birch) with longer-lived species (white pine, white spruce, and white cedar) should increase the biomass stocks on these landscapes over time, although short-term impacts may be negative due to removal of short-lived species. The majority of the carbon in forested landscapes is usually contained in the aboveground biomass, with lesser amounts in the soil and roots, and carbon sequestration monitoring protocols in these systems should be designed accordingly. For the duration of this monitoring effort, changes in soil carbon pools are presumed to be negligible in comparison to the predicted increase in aboveground biomass.

The Manitou River site has complex landscapes with a mixture of upland, wetland, and peatland sites and a mixture of forest types associated with these landscape microsites. Consequently, the silvacultural practices employed on these landscapes must also be adapted to spatial differences in the landscapes and forest. Likewise, any monitoring system designed to determine the impact of this adaptive management strategy on net carbon sequestration should also account for these differences in site, forest, and management.

Because the integrative silvacultural practices represent a change in management, one has to measure comparative differences between the "treatment" (the new management protocols) and "business as usual" (control sites where current management practices would continue. If measurement methods similar to the FIA methods are used to monitor the treatment sites, then the results from these sites may be compared to other sites outside of the treatment area that are managed under current guidelines or protocols. Numerous sites throughout the region are already being assessed in the existing forest inventory conducted every five years. If sufficiently similar sites maintained under current management strategies can be identified in the FIA database, it might be possible to use the FIA data for those sites to represent the "control sites", thus eliminating the need and expense of monitoring a series of control sites.

We recommend establishment of monitoring sites utilizing forest mensuration techniques similar to the FIA sites but at a significantly higher intensity. These sites should accommodate all significant landscape / forest / management combinations in order to accurately assess changes in the ecosystem carbon pools. Baseline measurements should also be made for soil organic carbon at each monitoring location for the purpose of making future comparisons.

Project Title: Carbon benefits in the Prairie Pothole Region

Project Sponsor: Bois de Sioux River Watershed
Partners: Stevens County Soil and Water Conservation District, Red River Flood Damage Reduction Working Group, MN Board of Water and Soil Resources, US Fish and Wildlife Service, Ducks Unlimited, and local landowners.

Project background: The Prairie Potholes, an immense region in north central United States, is considered one of the most important wetland areas in the world and home to approximately 50% of the North America's migratory waterfowl. In the 1980s, sharp declines in waterfowl populations ignited a national effort to protect and restore prairie pothole wetlands across the region, including northwestern Minnesota. Federal, state, and local governments, often in partnership with private conservation organizations, work with thousands of landowners to restore wetlands for wildlife habitat, flood reduction, water quality improvement, and other purposes. In Stevens County, approximately five thousand acres of wetlands and prairie buffers have been restored on private lands since 2006. What is the carbon sequestration benefit of wetland restoration, its costs and ancillary benefits, and compatibility with primary objectives? A demonstration project with Stevens County Soil and Water District and the Bois de Sioux Watershed District will look at carbon aspects of wetland restorations and their potential role in GHG reduction efforts.

Carbon demonstration plan:

(1) Establish baseline conditions and document design and operation of project. Document boundaries, baselines, and land use history. Document site preparation, construction, planting/seeding, and other activities

(**2) Assess changes in carbon sequestration and co-benefits.** Conduct field survey to estimate carbon stocks in project area. Monitor selected primary and secondary effects. Identify and test use of indicators of desirable/undesirable effects.

(3) Determine eligibility and requirements of incentive programs and test applicable management and accounting protocols. Evaluate applicability of public and private incentive programs, including carbon offset programs. Apply appropriate carbon accounting protocols to document carbon stock changes and other benefits associated with conversion of agricultural fields to wetlands and prairie. Analysis will include risk assessment of permanence and leakage to create a performance standard for similar projects in the area. Develop monitoring and reporting plan.

(4) Track costs and returns. Document time and money required to conduct project and verification requirements. Document income streams.

(5) Education and outreach. Hold annual field days for interested public on carbon stocks and changes resulting from project, methods of accounting, and other information.

Carbon sequestration monitoring plan:

Replacing annual row crops with perennial grasslands and/or wetland vegetation and re-establishing natural hydrology is widely recognized as having a high potential to increase carbon sequestration. Micrometeorological flux measurements are the most reliable method for determining carbon sequestration in wetland landscapes.

If wetland sites are part of flood reduction projects and subjected to annual flooding, this will pose problems for monitoring efforts. Inundation of these areas with floodwaters will cause significant sediment accumulation, highly confounding direct measurements of soil carbon stocks by soil sampling, and making it impossible to interpret results of such a study. The most likely scenario for monitoring carbon sequestration in these landscapes is to use micrometeorological flux methods, but to remove all equipment late in the fall or prior to spring thaw. While this process will produce large gaps in the data, soil microbial activity should be low during the periods of flooding and the winter periods prior to flooding and the overall effects on sequestration measurements should be minimal.

Additional effort will be needed to find a suitable control site, to ensure that the electrical supply will withstand flooding, and other concerns. If the sites are not subjected to annual flooding, then these caveats do not necessarily apply.

Project Title: Driftless Area Cover Crops Study

Project Sponsor: Minnesota Department of Agriculture
Partners: Farmer cooperators, Zumbro River Watershed Partnership, Fillmore SWCD, Basin Alliance for Lower Mississippi, Great Lakes Living Cover Initiative, MN Board of Water and Soil Resources, UMN Dept of Soil, Water, and Climate, UMore Park (Rosemount), USDA-Agricultural Research Services

Project background: Inclusion of winter cover crops in corn-soybean rotations and use of continuous living cover are being investigated as ways to protect soil from erosion, increase soil organic matter and quality, and reduce loads of sediment and nutrients in surface waters. These benefits are particularly important in livestock regions where use of corn stover as cattle forage has greatly reduced the amount of crop residues that contribute to and protect soils. An active team of researchers and farmer-cooperators has been working to expand use of cover crops in the state. This demonstration project would build upon previous work of this team and focus attention on the carbon sequestration benefits of cover crops. It would be conducted in four pairs of farm fields in the Zumbro River watershed.

Carbon demonstration plan:

(1) Establish baseline conditions and document design and operation of project. Document boundaries, baselines, and land use history. Document site preparation, establishment, and management of winter rye cover cropping system.

(**2) Assess changes in carbon sequestration and co-benefits.** Conduct field sampling of soil carbon and biomass in paired farm fields to determine carbon impacts. Identify and test use of soil quality indicators and its applicability to soil carbon. Link field data with micrometeorological carbon measurements produced in region. Monitor selected primary and secondary effects, including storm runoff, nitrate leaching, erosion, and water quality. Rainfall simulations will be correlated with in-stream monitoring data in watersheds.

(3) Determine eligibility and requirements of incentive programs and test applicable management and accounting protocols. Evaluate applicability of public and private incentive programs, including carbon offset markets. Apply appropriate carbon accounting protocols to document carbon stock changes and other benefits of winter rye cover crops in corn-soybean systems. Analysis will include risk assessment of permanence and leakage to create a performance standard for similar projects in the area. Develop monitoring and reporting plan.

(4) Track costs and returns. Document financial requirements of cover cropping systems compared to non-use. Document profitability of cover cropping systems.

(5) Education and outreach. Farmer-led meetings and annual field days will be held to develop and report field methods and the impacts of cover crops.

Carbon sequestration monitoring plan:

A combination of micrometeorological flux methods and biomass harvest measurements will provide the best potential to measure changes in soil carbon in these agricultural settings over a relatively short timeframe. Both treatment (sites including cover crops in the corn-soybean rotation) and control (excluding cover crops) sites will need to be established and monitored. Similar research is already being conducted by USDA-ARS and University of Minnesota researchers at the UMORE Park Research and Outreach Center at Rosemount, MN, to determine the carbon sequestration inputs of cover crops to a corn-soybean rotation. An additional site might be required to determine the net effect when stover is removed. A larger project on the inclusion of cover crops is being conducted by the MN Department of Agriculture in the Zumbro River watershed. USDA-ARS and U of M faculty are also working with this particular project.

Although micrometeorological flux measurements can be completed in a single annual cycle, sites should be maintained for several years in order to determine the effect of inter-annual climate variations on the rates and variability of these carbon sequestration practices. A rigorous soil sampling scheme should be established at the Zumbro River watershed site and at each micrometeorological sampling site (both treatment and control sites) to provide a baseline for longer term soil carbon monitoring.

Project Title*:* Koda Energy Biofuels Production Project

Project sponsor*:* Rahr Malting
Partners: Shakopee Mdewakanton Sioux Community, Rural Advantage, UMN Department of Agronomy, UMN Center for Natural Resource and Agricultural Management

Project background: In 2006, and Rahr Malting and the Shakopee Mdewakanton Sioux Community formed Koda Energy to generate electricity and heat by burning agricultural byproducts and dedicated energy crops. Koda Energy expects to be fully operational in late 2008 and, over time, to supply much of energy needs of the SMSC and Rahr facility. The specific fuel mix burned by Koda will be a blend of waste from malting and food processing, wood chips, biosolids, switchgrass, and other native grass species. The utilization of prairie plants by Koda Energy and similar facilities would be in important driver of conversion of marginal cropland to perennial grassland cover and energy crops, with important implications for rural income and sustainability. Besides providing a local, renewable source of energy, conversion of marginal croplands to perennial biofuels would increase carbon sequestration.

Carbon demonstration plan:

(1) Establish baseline conditions and document design and operation of project. Document boundaries, site conditions, and land use history. Document site preparation, conversion of cropland to grassland, fertilization, and other management practices. Document harvest procedures and yields.

(**2) Assess changes in carbon sequestration and co-benefits.** Document carbon stock changes associated with changes in vegetative cover. Monitor selected primary and secondary effects.

(3) Determine eligibility and requirements of incentive programs and test applicable management and accounting protocols. Evaluate applicability of public and private incentive programs, including carbon offset markets. Conduct appropriate carbon accounting protocols. Analysis will include assessment of permanence and leakage to create a performance standard for similar projects in the area. The study will also assess additionality requirements for carbon offset transactions. Develop monitoring and reporting plan.

(4) Track costs and returns: Document time and money required to conduct project and marketing requirements. Document income streams from biofuel harvest and other sources.

(5) Education and outreach: Hold annual field day for farmers and interested public on carbon stocks and changes resulting from conversion of annual croplands to biofuel systems, methods of accounting, and other information.

Carbon sequestration monitoring plan:

Carbon sequestration in grasslands is mainly associated with increases in soil carbon storage, and has been well-studied. The harvest of biomass represents a significant modification of this practice, however, and may substantially affect the carbon sequestration rates of this practice. Monitoring of carbon sequestration in grasslands is best addressed in the short term by micrometeorological flux methods in association with biomass harvest measures.

A significant level of expertise is required to operate and interpret the data obtained from a micrometeorological system. In addition, these systems require a considerable amount of attention to keep them running well. Currently in the state there are only 4 or 5 individuals working with these systems. From an operational and a financial viewpoint, it is desirable to cluster monitoring sites together to limit the amount of travel time between sites and to provide greater oversight for the equipment. From an environmental perspective, it would be desirable to have more sites that would encompass the greatest variability in climatic and other environmental conditions to provide the most robust dataset. The proposed network model, which has a western and an eastern site, is probably a reasonable compromise.

An additional potential for carbon sequestration is the addition of bio-char to soils. Bio-char (also called "black carbon") is a by-product of biomass pyrolysis techniques wherein the materials are heated to produce and release volatile organic gases and liquids that are then used for fuels. These materials have advantages over burning solid biomass in that they are easier to handle and more controllable. Bio-char is a residue of this process and consists, essentially, of materials similar in most respects to charcoal. Microbes have great difficulty degrading bio-char and it is predicted to be stable in soils for decades to millennia. If bio-char is or becomes available, it would be highly desirable to develop an additional monitoring site at one of these locations to observe its effect on total carbon dynamics or at least to perform soil incubation studies to determine the relative rate of bio-char decomposition.

Although micrometeorological flux measurements can be completed in a single annual cycle, sites should be maintained for several years in order to determine the range and variability associated with these carbon sequestration practices. A rigorous soil sampling scheme should be established at each micrometeorological sampling site (both treatment and control sites) to provide a baseline for longer term (25 - 100 years) soil carbon monitoring. In this instance, since we are interested in the conversion from a corn-soybean row crop rotation to a perennial grass / prairie biofuel system, a nearby corn-soybean field would be used as the control site.

Project Title: Minnehaha Creek Urban Forestry

Project Sponsor: Minnehaha Creek Watershed District
Partners: Minnesota DNR ReLeaf Program, Great River Greening, Tree Trust, and municipalities, park authorities, and commercial property owners in the watershed

Project background: The Minnehaha Creek Watershed District (MCWD) is in the process of identifying projects, programs, and other management strategies to reduce nutrient loading and export to downstream waters; reduce annual stormwater volume and peaks; and to address conservation priorities and 'green infrastructure' opportunities in the watershed. The MCWD is interested in the multiple benefits of urban reforestation that address watershed concerns and simultaneously reap the benefits of GHG reduction from increased carbon sequestration. The MCWD would like to undertake an evaluation of the effects of reforestation and reestablishment of native habitats on water quality and carbon sequestration in one sub-watershed in the rural-urban transition zone. Unlike other projects in this program, the MCWD would begin with a planning process to identify optimal areas for reforestation and implementation needs for reforestation activities.

Carbon demonstration plan:

(1) Document baseline conditions. Document current and historical land use. Conduct inventory-based measures of carbon stocks in project area.

(2) Evaluate the importance of landscape position on tree growth and restoration success and identify geographic areas where success will be maximized. Work with advisory group and published literature on factors restoration success. Investigate techniques for correlating carbon emissions and sequestration to land uses that increase or decrease stormwater runoff. If this relationship can be established, the benefits of land use change for both water quality and carbon emission reductions could be estimated.

(3) Determine eligibility and requirements of alternative incentive programs. Identify mechanisms for implementation of reforestation activities through projects and programs. Identify policy, rules, and ordinance changes necessary to maintain watershed canopy cover over time. Select and apply carbon accounting protocols to project carbon stock changes and other benefits associated with changes in forest cover. Analysis will include risk assessment of permanence and leakage that be used as a performance standard for similar projects. Develop monitoring and reporting plan.

(4) Conduct cost-benefit analysis of watershed reforestation. Identify the value per tree and per acre of forestation for the benefit of carbon removal, water quality, and conservation.

(5) Education and outreach. Hold technical and public education meetings to advise project and provide information on urban reforestation as a carbon reduction strategy.

Carbon sequestration monitoring plan:

Measurement of carbon sequestration benefits associated with urban forestry is restricted to accrual of aboveground standing biomass and woody debris. Changes in soil carbon are extremely difficult to measure in urban sites due to the high degree of disturbance commonly associated with urban construction and development activities and the enormous variability attributed to it.

Urban mensuration techniques can be applied in a longitudinal fashion to observe differences in total standing biomass over time, thus providing measures of net carbon sequestration resulting from these activities. One may assume that the initial condition represents the baseline or control condition and that changes in carbon stocks are therefore the result of changes in management techniques.

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Appendix A

Opportunities for Improved Carbon Management, by Minnesota Eco-region	
Eco-region	**Complementary land use/management**
Northwest Tallgrass Aspen Parklands	✓ Grassland establishment (native and perennial) ✓ Woody and grass biofuel production ✓ Improved pasture and hayland management[1] ✓ Wetland restoration
Northeast Mixed Forests	✓ Woody biofuel production ✓ Improved pasture and hayland management ✓ Enhanced stocking forest & shrublands ✓ Ecological restoration of public forests[1]
Central Broadleaf Forest	✓ Woody biofuel production ✓ Cover crops on annual row crops ✓ Afforestation / reforestation (restoring former forestland back to forest) ✓ Improved pasture and hayland management[1] ✓ Grassland establishment (native and perennials)
South and West Prairie	✓ Grassland biofuel production[1] ✓ Cover crops (south-central) ✓ Improved pasture and hayland management[1] ✓ Grassland establishment (native and perennial) ✓ Wetland restoration
Urban Areas	✓ Urban / community forests ✓ Wetland restoration ✓ Afforestation / Reforestation

[1] These land use/management practices are modifications of sequestration practices described in Anderson et al., 2008. Their actual carbon sequestration benefits depend on specific management changes. For instance, improved pasture and hayland management encompasses a range of practices affecting the density and diversity of vegetation and grazing intensity. Sequestration rates could vary widely depending on which of these changes are introduced. Carbon sequestration effects of such applications should be monitored.

Appendix 1. Protocols for monitoring of carbon sequestration in forests and in soils.

A. FOREST MENSURATION

Forest biometricians have developed measurement and statistical methods to determine the total quantity of biomass in various forest ecosystem components, such as standing timber, woody debris, and the shrub, forb, and grass layers. Additional relationships exist between aboveground biomass and belowground (root) biomass that allow for reasonably accurate estimation of root mass. These are (mainly) non-destructive techniques that can generally detect changes in forest biomass (and biomass C) within a 5 or so year time increment.

Materials to be Measured

With respect to forest biomass accretion, three vegetation strata will be measured; trees (including saplings), tall shrubs, and low shrubs and herbs (including ferns, grasses, and forbs). In addition, down woody materials, including coarse and fine woody debris, will be sampled.

Background

A detailed discussion of sampling procedures to be used to assess forest carbon and its change with time should be prefaced with a short discussion of the relative proportion of carbon in various components, and their potential change with time. In forests, vascular aboveground biomass (about half of that biomass is carbon) is dominated by trees. A series of examples from three sets of data from forests in Minnesota make that very clear: (1) conifer plantations of varying ages sampled in northern Minnesota (Ohmann 1984); (2) forested wetlands sampled across central and northern Minnesota (Swanson and Grigal 1991); and (3) upland forest stands sampled within the Boundary Waters Canoe Area (Ohmann and Grigal 1985). All these data show similar distributions of biomass among vegetation strata (Figure Forest-1).

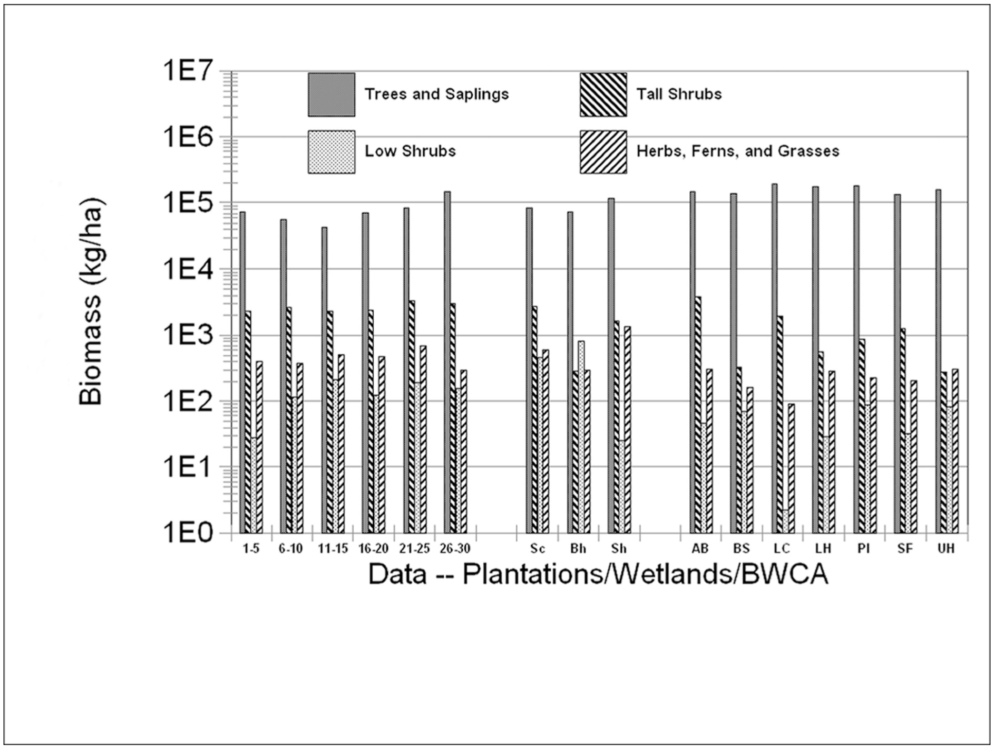

Figure Forest-1. Vascular aboveground biomass distribution among vegetation strata of forest stands from Minnesota. Bars to left represent 53 conifer plantations from northeastern Minnesota, classified into six groups based on time (years) since establishment (Ohmann 1984). Central bars represent 70 forested wetlands sampled across central and northern Minnesota, classified as Sc = conifer swamp, Bh = high-density treed bog, and Sh = hardwood swamp (Swanson and Grigal 1991). Bars to right represent 194 upland forest stands sampled within the Boundary Waters Canoe Area, re-classified as AB = aspen-birch, BS = black spruce, LC = lowland conifers (predominantly northern white cedar and balsam fir), LH = lowland hardwoods (predominantly ash and elm), PI = pine, SF = spruce-fir, and UH = upland hardwoods (maple, basswood) (Ohmann and Grigal 1985).

In all cases, biomass of trees and saplings is one to two orders of magnitude higher than that of any other strata, at about 100 t ha^{-1} (Figure Forest-1). The tall shrub stratum ranges around 2 t ha^{-1}, with generally greater mass in the plantations (Figure Forest-1). Low shrubs contribute about 0.1 t ha^{-1}, and are most important in the wetland forests (Figure Forest-1). Finally, non-woody forbs, ferns, and grasses contribute about 0.5 t ha^{-1}, with variable distribution among the forest types but greater mass in the plantations and wetlands (Figure Forest-1).

This distribution of biomass among vegetation strata, with well over 95 percent in the trees and sapling, illustrates the importance of accurately sampling tree biomass, and conversely, the lesser importance of the other strata in terms of a carbon inventory. Uncertainty of ✂ 10 percent in tree biomass is greater than the sum of the biomass of all the other vascular strata. That knowledge can be used to allocate resources in sampling forest biomass.

Estimated biomass of woody debris ranges from less than 10 to 40 t ha^{-1} for forests in eastern and continental areas of North America (Duvall and Grigal 1999; McCarthy and Bailey 1994; Muller and Liu 1991; Sturtevant et al. 1997; Tyrell and Crow 1994). An inventory of woody debris in 563 forest stands in northcentral Minnesota found an average of about 23 t ha^{-1}, evenly divided between snags (standing dead trees) and logs (dead wood on the forest floor) (unpublished data). The range of debris biomass among forest types was between about 10 and 30 t ha^{-1} (Figure Forest-2). Because about 10 percent of the aboveground biomass in forest stands in Minnesota is in woody debris as logs (Figure Forest-1, Figure Forest-2), any reasonable carbon inventory requires accurate estimates of biomass in woody debris. That estimate is more important than that in any vegetation strata except trees.

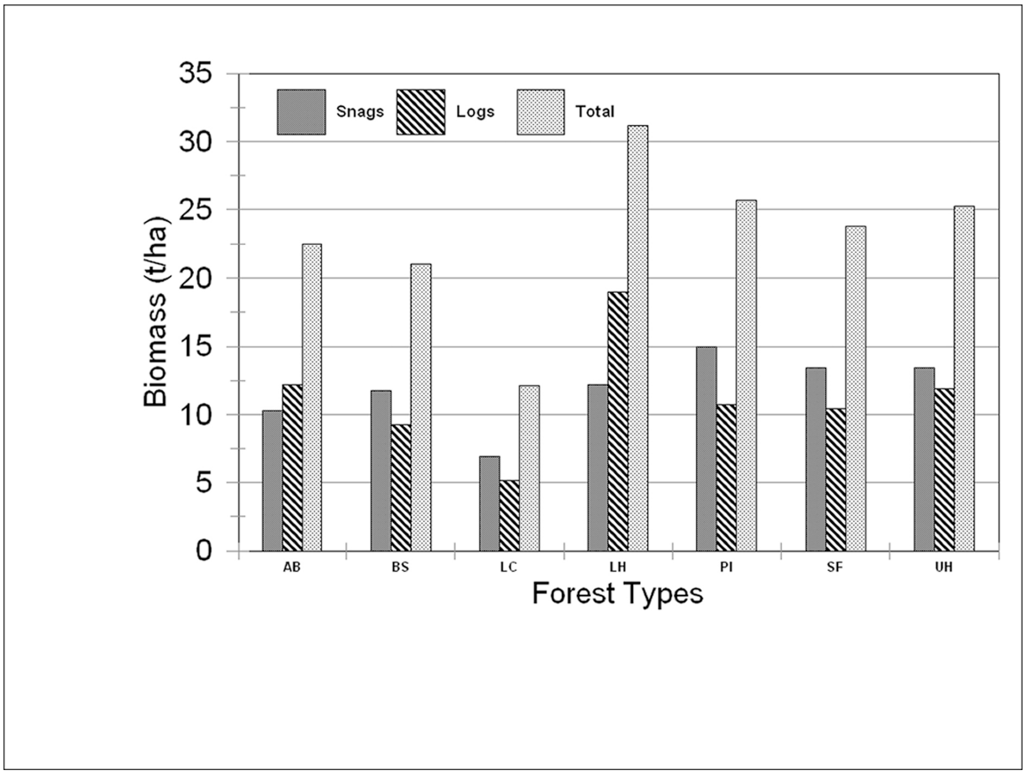

Figure Forest-2. Biomass distribution in woody debris among 563 forest stands from north-central Minnesota. AB = aspen-birch, BS = black spruce, LC = lowland conifers (predominantly northern white cedar and balsam fir), LH = lowland hardwoods (predominantly ash and elm), PI = pine, SF = spruce-fir, and UH = upland hardwoods (maple, basswood) (unpublished data).

Field Methods

Basis of Protocols

The relative size of the carbon pools of the various components of the forest ecosystem, in conjunction with two criteria that: (1) where feasible, standard methods should be used to allow for greater comparability of the results of these monitoring studies with those obtained from other studies of C sequestration; and (2) sampling methods should be sufficiently documented so that they may be replicated in the future by individuals not involved in the initial study, leads to a proposal to base the forest biomass (C) sampling on the USDA Forest Service's Forest Inventory and Analysis (FIA) program. This program has been in continuous operation since 1930 (http://fia.fs.fed.us/library/fact-sheets/default.asp, assessed 26 October 2008). The FIA program has a very broad mission, and collects, analyzes, and reports information on the status and trends of forests in the U.S.: how much exists, where it exists, who owns it, and how it is changing, as well as how the trees and other forest vegetation are growing and how much has died or been removed in recent years. These activities have led to a well-documented set of protocols, including methods to analyze uncertainty (http://www.fia.fs.fed.us/library/field-guides-methods-proc/, assessed 28 October 2008).

Because the primary goal of the current project, monitoring changes in forest biomass over time at a few selected sites, differs somewhat from the goals of FIA, their protocols will require minor modifications for this application.

Sample Design and Plot Layout

Sample Design

The current FIA program consists of three phases. Phase 1 uses remotely sensed data such as aerial photographs and satellite imagery for initial plot measurement and stratification. Phase 2 consists of field sampling at an intensity of about one site for every 2500 ha. The major data that are collected at that intensity relate to the tree strata. Phase 3 consists of a subset of Phase 2 plots (approximately one for every 16 plots) that are measured for a broader suite of attributes, including tree crown conditions, lichen community composition, understory vegetation, down woody debris, and soil properties (Sampling and Plot Design.pdf, http://fia.fs.fed.us/library/fact-sheets/default.asp, assessed 26 October 2008).

Sampling changes in forest biomass over time at a few selected sites, as in the current work, will require modifications of methods used in Phase 3, but with a much higher intensity of sampling per unit area. Sampling will be directed at trees, tall shrubs, low shrubs, herbs (including ferns, grasses, and forbs), and woody debris.

At each forest site/treatment, at least three plots will be established. This is a much higher intensity than that used by FIA, but is necessary to provide some measure of uncertainty of the ultimate estimates. Depending on budgets, more plots per site/treatment could be established.

Plots will be located by a restricted randomization scheme. At each site/treatment, a rectangular grid will be established, with each grid point a possible plot center. Portions of the grid that represent desired conditions will be selected *a priori*. In other words, unrepresentative areas (because of differing soil, vegetation, topographic position, etc.) will be excluded from potential sampling. Three (or more) plot centers will then be randomly located among the acceptable grid points. They will be located by GPS, and plot and subplot centers (see below for layout) will be permanently marked by metal re-bar.

Plot Layout

Each plot in the FIA sampling scheme consists of four subplots (Figure Forest-3). This layout will also be used to assess changes in forest biomass over time, but some of the details of the layout will not be used. For example, because of the strong interest in C change in soil, sampling for that component will be carried out using a different, more intensive, scheme. Similarly, the "Lichens plot" will not be used; lichens and mosses will be sampled as part of the forest floor sampling. Those samplings are discussed in other portions of this document.

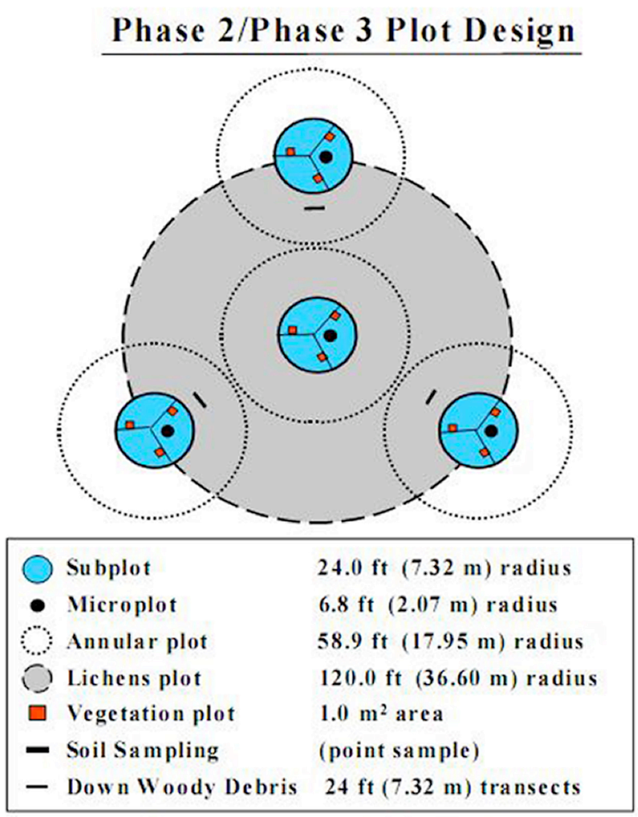

Figure Forest-3. Schematic layout of FIA plot layout used for Phase 2 and Phase 3 sampling. Subplots are oriented around the central subplot (subplot 1) at 360° (subplot 2), 120° (subplot 3), and 240° (subplot 4), at 36.6 m from center to center (from Sampling and Plot Design.pdf, http://fia.fs.fed.us/library/fact-sheets/default.asp, assessed 26 October 2008).

Tree Sampling

Trees are sampled on each subplot (7.32 m radius). FIA was originally established to provide inventories of forest resources for industrial use, and that remains one of its foci. As a result, the size criterion for trees versus saplings, and the resulting difference in their sampling, retain some of that orientation. However, for compatibility and comparability of the results of our monitoring studies with those obtained from other studies of C sequestration, that criterion will be retained.

Detailed procedures for tree sampling can be found in the National Core Field Guide, Version 4.0 (http://www.fia.fs.fed.us/library/field-guides-methods-proc/, assessed 28 October 2008). Briefly, trees at least 5.0 inches (12.7 cm) in diameter at breast height are measured within the subplot. These include all live and standing dead trees. Trees with a diameter at least 1.0 inch (2.54 cm) but less than 5.0 inches are termed saplings, and are sampled within the microplot (2.07 m radius). The center of the circular microplot is 90☜ and 3.7 m offset from point center of each subplot. All live saplings are measured. At successive samplings over time, all saplings that grow into each microplot thereafter are included until they grow to 5.0 inches or larger, at which time they are measured within the subplot and provided with a positional reference.

Tree measurements include species, diameter, height, and location (azimuth and distance from subplot center). Additional protocols, such as the definition of standing dead, can be found in the field guide (National Core Field Guide, Version 4.0).

Tall Shrub Sampling

Although the FIA estimates percent cover of vegetation by both height stratum and by species, they do not attempt to estimate biomass of non-tree vascular vegetation (Phase 3 Field Guide - Vegetation Diversity and Structure, Version 4.0, October, 2007, http://www.fia.fs.fed.us/library/field-guides-methods-proc/, assessed 28 October 2008). The FIA sampling scheme will therefore be modified to allow estimation of biomass of tall shrubs (defined by FIA as woody plants with height > 0.5 m at maturity – Phase 3 Field Guide).

Three vegetation plots – also termed quadrats in some of the FIA documentation – are located on each subplot (Figure Forest-3). Plots are 1 m^2 (3.28 x 3.28 ft). They are located on the right sides of lines at azimuths of 30°, 150°, and 270° from the subplot centers. Two corners of each quadrat are permanently marked at 15 and 18.3 feet (4.57 and 5.57 m), horizontal distance, from the subplot center.

Detailed tall shrub data will be collected on one quadrat per subplot, that at 30°, and more extensive tall shrub data on the other two quadrats. The detailed data will be a tally of all tall shrub stems by diameter class, and the extensive data will be simply height and cover. This sampling is based on the lesser importance of tall shrubs to total aboveground vascular biomass.

Stem Tally

On the selected quadrat (that at 30°), the diameter at 15 cm aboveground of all woody stems with a diameter at breast height of < 2.5 cm will be measured as a semi-continuous variable in 2.5 mm classes with a template and tallied by size and species (Figure Forest-4).

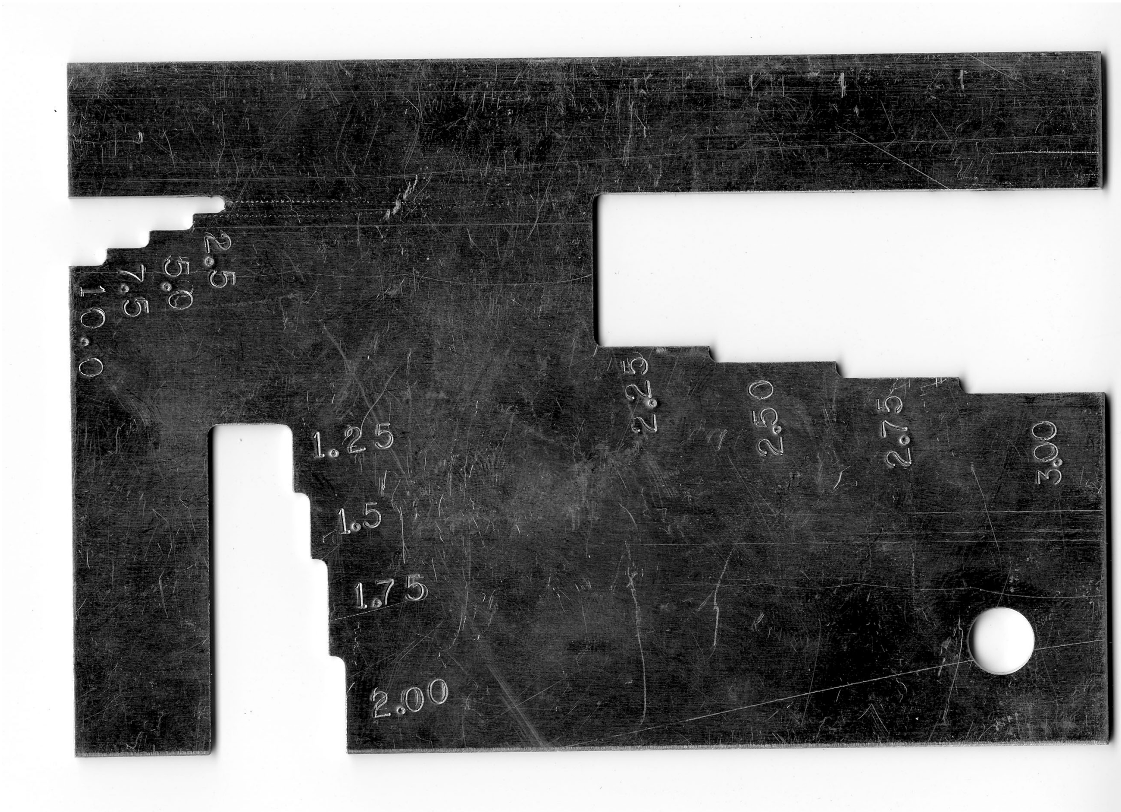

Figure Forest-4. Template used to measure shrub diameter at 15 cm aboveground as a semi-continuous variable in 2.5 mm classes.

Extensive Data

On all three quadrats, extensive data for tall shrubs will be collected. These data will be canopy cover of tall shrubs by height classes, and will generally follow FIA protocols. Canopy cover is based on a vertically-projected polygon described by the outline of the foliage, ignoring any normal spaces occurring between the leaves of plants (Phase 3 Field Guide). A rapid canopy cover estimate is made, ignoring overlap among species, and consists of the total canopy cover of the foliage of all tall shrubs by layer above the ground surface. Cover will be estimated in the following classes: 1-5%, 6-10%, 11-20%, 21-40%, 41-60%, 61-80%, and 81-100%. Two heights classes will be used; > 0.5 to 2 m and > 2 to 5 m. These approximately correspond to the FIA layers of > 2 to 6 ft and > 6 to 16 ft.

Low Shrub and Herb Sampling

Low shrubs (defined by FIA as woody plants with height < 0.5 m at maturity – Phase 3 Field Guide) and herbs, including ferns, grasses, and forbs, will be sampled similarly. As with tall shrubs, FIA does not attempt to estimate biomass of non-tree vascular vegetation (Phase 3 Field Guide - Vegetation Diversity and Structure, Version 4.0, October, 2007, http://www.fia.fs.fed.us/library/field-guides-methods-proc/, assessed 28 October 2008).

As with this modification of the FIA sampling scheme, biomass estimates for low shrubs and herbs will be focused on the three vegetation plots (quadrats) on each subplot (Figure Forest-3). In this case, the same sampling scheme will be used for all quadrats. As with tall shrubs, the intensity of sampling is based on the lesser importance of low shrubs and herbs to total aboveground vascular biomass.

Cover Estimates

Specifically, canopy cover will be estimated for low shrubs, ferns, forbs, and grasses (separately) within each of three height classes as subdivisions (approximate halving) of FIA vegetation layers. Height classes will include 0 - 0.25 m and > 0.25 - 0.5 m (the sum roughly corresponding to the 0 - 2 ft layer), and > 0.5 - 1.0 m (half of the > 2 to 6 ft layer). Total canopy cover and canopy cover within each height class will be estimated, but the majority of life forms will probably have canopy cover in only one layer, so that the total and layer canopy covers will be identical. Canopy cover is based on a vertically-projected polygon described by the outline of the foliage, ignoring any normal spaces occurring between the leaves of plants. The following canopy cover classes will be used: 0, <1, 1-5%. 6-10%, 11-20%, 21-40%, 41-60%, 61-80%, and 81-100%. The 0 class will be used for plants rooted in the quadrat but with no foliage in the height class. Cover for any height class cannot be greater than the total cover for that life form.

Clipping

Cover data will be converted to biomass estimates using locally-developed relationships (see **Numerical Methods**). To obtain the data for these relationships, biomass will be determined and cover estimated for each life-form on one auxiliary quadrat per subplot. These auxiliary quadrat (clip plots) will be identical in size (1 m^2) to the quadrats used for sampling low shrubs and herbs, and will be located on the right sides of a line at an azimuth of 90° from the subplot centers. Two corners of each auxiliary quadrat will be temporarily marked at 15 and 18.3 feet (4.57 and 5.57 m), horizontal distance, from the subplot center. In subsequent samplings over time, the azimuth will shift to 210° and 330° from the subplot centers. If additional sampling is carried out, azimuths of 60°, 180°, and 300° from the subplot centers will be used.

Biomass will be determined on the clip-plots by clipping each life-form at ground level and returning the material to the laboratory for oven-drying and determining mass. Canopy cover will be estimated as on the permanent sample plots.

Sampling Down Woody Materials

Down woody materials can be an important pool of carbon in forest ecosystems. Down woody material is dead material on the ground in various stages of decay, and for this inventory it includes coarse woody debris (CWD) and fine woody debris (FWD). In the case of sampling these materials, as with trees, the FIA protocols will nearly wholly be followed (Phase 3 Field Guide - Down Woody Materials, Version 4.0, October, 2007, http://www.fia.fs.fed.us/library/field-guides-methods-proc/, assessed 28 October 2008).

Briefly, the basis of the sampling of down woody materials are linear transects wherein material that intersects the transect line is inventoried   That procedure will be briefly described below, but details will be found in the field guide (Phase 3 Field Guide - Down Woody Materials). In the sampling, CWD includes downed, dead tree and shrub boles, large limbs, and other woody pieces that are severed from their original source of growth and on the ground. CWD also includes dead trees (either self-supported by roots, severed from roots, or uprooted) that are leaning > 45 degrees from vertical. As the name implies, CWD is generally larger material (pieces > 3.0 inches (7.5 cm) in diameter at the point of intersection with the transect). Material smaller than CWD is considered FWD, and includes downed, dead branches, twigs, and small tree or shrub boles that are not attached to a living or standing dead source. It can be connected to a larger branch, as long as this branch is on the ground and not connected to a standing dead or live tree. Only the woody branches, twigs, and fragments that intersect the transect are counted. More detail on the definitions and criteria for each class can be found in the field guide (Phase 3 Field Guide - Down Woody Materials).

Sampling for CWD is along three transects that originate at the subplot center and extend 24.0 ft horizontal distance (the radius of the subplot) at azimuths of 30☜, 150☜, and 270☜ (Figure Forest-3). In the case of FWD, only one transect is established on each subplot, along the 150☜ azimuth. Because FWD is generally present in higher densities than CWD, a shorter transect is used. The transect begins at 14 ft (slope distance) from the subplot center and extends out either 6 ft (for small – 0 to 6 mm diameter – and medium FWD – > 6 mm to 24 mm) or 10 ft (for large FWD – 25 mm to 75 mm).

Individual pieces of CWD intersected by a transect are tallied by measuring the diameters at the point of intersection, and at the small end and the large end (depending on decay class).   Total length between those latter two diameters is also recorded. The decay class of the CWD (1 = sound, freshly fallen, intact logs; 2 = sound, mostly intact; 3 = heartwood sound; 4 = heartwood rotten; 5 = no structural integrity) is noted (details in Phase 3 Field Guide - Down Woody Materials). In the case of FWD, individual diameters are not recorded but simply the counts in each of the three size classes are recorded.

Numerical Methods

The data that are collected will be summarized and used to estimate biomass and related carbon mass.

Trees

<u>Aboveground</u>

Aboveground tree biomass is usually estimated through the use an allometric equation

$$M = a \times D^b \qquad (1)$$

where M is aboveground tree biomass and D is tree diameter, usually measured at 1.3 m aboveground (Kittredge 1944, Ter-Mikaelian and Korzukhin 1997). The standard method to obtain estimates for *a* and *b* in Eqn. (1) is by least-square regression of data of M and D pairs measured from destructively sampled trees that represent the diameter range of the stands under investigation. This is a laborious and time-consuming process. As a result, applicability of equations beyond the specific population of trees that were sampled has been explored and tested. For example, theoretical models have been developed to describe the M-D allometry. One model assumes the presence of an M-D scaling relationship irrespective of species, site and genetic factors, wherein *b* is = 8/3 (2.67) and *a* = 0.10 (West et al. 1999). A recent analysis of 279 studies indicated an average empirical value of *b* = 2.368 and *a* = 0.14 (Zianis 2005). These discussions are cited to indicate a source of uncertainty in tree biomass estimates.

Although ideally both *a* and *b* should be developed locally for any stand-level biomass estimates, the cost-benefit of such an approach must be considered. If one accepts the premise that variability in *a* and *b* are very important, then a "new" relationship should be developed at each site and time. There is, for example, a suggestion in the literature that different *b* values are necessary for different growth stages of trees (juvenile, adult and mature) (Pilli et al. 2006).

An alternate approach is to use the series of biomass estimation equations from Alemdag (1983, 1984). Those equations, based on trees sampled in Ontario, encompass all the species likely to be found in Minnesota. The equations are similar to Eqn. (1), but use both tree dbh and total height as independent variables. Although tree height may not be measured as accurately as diameter in standing trees, it may help distinguish biomass differences in different growth stages. There is generally a strong height-diameter relationship among forest trees, and this may introduce issues such as some questions in propagation of uncertainty (Zianis 2008). In summary, however, inclusion of tree height (an FIA variable) in estimating tree biomass probably contributes to accuracy and precision. Because our primary interest is in longitudinal studies, the same suite of equations is likely sufficient to detect differences in biomass over time.

Belowground

Biomass estimation equations for tree roots are relatively uncommon in the literature, and there is no comprehensive set of equations for Minnesota species. An alternative is to base belowground biomass estimates on data from Santantonio et al. (1977), who tabulated root biomass estimation equations from a large number of studies and also provided a figure with individual data points showing the relationship between tree dbh and root mass, on an estimation equation for root mass from New Hampshire that was based on aboveground mass (Whittaker and Marks 1975), and from an estimation equation from Minnesota based on diameter (but with only 17 observations) (Perala and Alban 1994). An expression of root mass as a function of tree diameter, computed as the average of the literature sources, yields an expression similar to Eqn. (1) but where M is belowground tree biomass and D is tree diameter, and where *a* = 0.031 and *b*

= 2.39. Comparison with the average empirical values from Zianis (2005), cited above, indicates that although tree root biomass varies with diameter, it is approximately 22 percent of aboveground biomass or about 18 percent of total tree biomass.

Tall Shrubs

There are extensive data from northern forests that relate tall shrub stem diameter to biomass (Telfer 1969, Grigal and Ohmann 1977, Ohmann et al. 1976, Brown 1976, Roussopoulos and Loomis 1979, Ohmann et al. 1981, Connolly and Grigal, 1983). Most of the equations describing these relationships have been summarized by Smith and Brand (1983). Many of the equations are based on shrub diameter at 15 cm aboveground, and in many cases the diameter is "measured" as a semi-continuous variable in 2.5 mm classes (using a template – Figure Forest-4). The allometric relationship is

$$M = a \text{ x } D^b \qquad (2)$$

as in Eqn. (1), except in this case where M = tall shrub biomass and D is shrub diameter class in mm or cm.

When using a template for measuring the shrub diameter and developing the allometric relationship, as described in the field methods, D in Eqn. (1) is not the shrub diameter but the maximum size of that diameter class (e.g., diameters in the class 10.0 to 12.5 mm are all less than 12.5 mm). Some data have indicated that this approach tends to inflate the estimated total biomass if there are many stems in the smallest size classes (Balogh 1983). An approach that has been used is to fit the diameter-density distributions for individual shrub species to a linearized power function

$$\ln (N) = c + d \ln (Dm) \qquad (3)$$

where ln (N) is the natural log of the estimated number of stems of that diameter class and ln (Dm) is the natural log of stem diameter class in mm or cm. The slope of this equation (*d*) for each species is the change in number of individuals with diameter. Using this approach, the expected number of individuals by diameter class was then estimated by Eqn. (3) and biomass was computed using Eqn. (2) (Ohmann and Grigal 1985).

Using the procedures described above, and the relevant species-specific biomass estimation equations from the literature (Smith and Brand 1983), biomass by species will be estimated for tall shrubs on each of the intensively-sampled quadrats. Tall shrub biomass has also been estimated by cover and height (e.g., Peek 1970), albeit for individual clumps of single species. Relationships will be developed (linear, allometric, simply broad classes?) between total tall shrub biomass and canopy cover/height from the intensively-sampled quadrats, and those relationships will be applied to the extensively-sampled quadrats within each site/location at each sampling time. The relationships will be developed with n = 12 (3 plots x 4 subplots/plot x 1 intensive quadrat/subplot).

Low Shrubs and Herbs

Biomass estimation equations, using canopy cover as the independent variable, have been developed for herbs, ferns, and low shrubs (Ohmann et al. 1981) and applied for stand-level estimates. Undergrowth biomass can be reasonably estimated by the relationship

$$\text{Mass} = e \times C^{f} \qquad (4)$$

where Mass = biomass, C is canopy cover in percent, and *e* and *f* are constants of the relationship. These equations are generally species-specific, but in the case of this inventory similar mathematical expressions will be used for each life-form. Locally-developed relationships (Eqn. (4)) will be developed for each site/location at each sampling time.

These relationships will be based on the data from the auxiliary clip-plots by clipping each life-form at ground level and returning the material to the laboratory for oven-drying and determining mass. Canopy cover will be estimated as on the permanent sample plots. For each life form, the relationships will be based on n = 12 (3 plots x 4 subplots/plot x 1 clip plot/subplot).

Understory Belowground Biomass

Although the magnitude of root biomass of understory vegetation is small compared to that of trees, some general estimates can be made using data from the literature. Reasonable ratios between biomass of roots and shoots are about 1.5 for tall shrubs and about 2 for herbaceous vegetation.

Down Woody Materials

Biomass and C content of woody debris is usually based on the calculation of volumes using techniques described by Van Wagner (1968). The biomass and C content is then estimated by combining the volume with estimates of density and C concentration of woody debris (e.g., as reported by Duvall 1997). Both density and C vary with decay class, and so the computation is carried out by decay class. For this study, FIA protocols and algorithms will be used.

Limitations of the method

Potential magnitude and sources of error

Unfortunately, there are numerous sources of error (i.e., uncertainty) in estimating forest biomass (C) change over time. These techniques require many field measurements, and measurement errors are a potential source of error. Translation of those measurements to biomass via various estimation equations also introduces error. Uncertainty in the equations may be related to their functional form, the precision of the estimation, and their applicability to a specific site(s).

Potential strengths and weaknesses

These methods are relatively inexpensive to implement and require no significant maintenance. This would not be the case if unique tree biomass estimation equations were developed for each site/time of sampling. A major weakness of biomass estimation is the estimation of belowground C.

Applicable timeframe of measurement

Biomass estimation techniques should be able to detect incremental changes in aboveground biomass, primarily of trees, occurring over about a five- to ten-year period. Shorter periods of observation require proportionally higher intensity of sampling and measurement.

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B. SOIL SAMPLING

Preliminary considerations

This project addresses questions about changes in a single plot and differences in change between two plots, where those two plots may have different treatments (Fig. Soil-1).

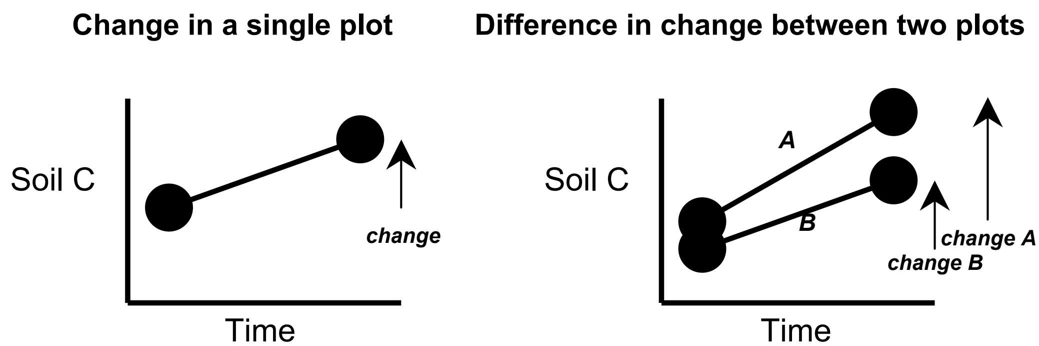

Figure Soil-1. Changes in a single plot vs. comparing changes between plots

The statistical observational unit is the plot. Soil sampling areas are subsamples within the plots. Comparison of single plots having different treatments does not allow conclusions about the treatments, only that the plots are different or not. Statistically based conclusions are valid only for the plots, although managers might choose to extrapolate (i.e., nonstatistically) to other locations. To address the question "Do different treatments differ in their magnitude of change?" would require multiple plots of each treatment with the treatments randomly assigned to the plots; that is beyond the scope of this study.

The plot may be adjacent to land-uses similar to the plot, or surrounded by other land uses. If surrounded by other land uses, there needs to be a decision about whether or not the plot should be divided a central measurement area and a buffer area.

Where to sample within the plot

The general sampling layout is to have multiple sampling areas within each plot and one or more sampling points within each sampling area (Fig. Soil-2). Future resampling may be conducted within the same set of sampling areas, which will yield higher statistical power if variability within a sampling area is much less than variability across the entire plot. However, if this is not the case, or if sampling areas cannot be exactly relocated, or if sampling areas have been disrupted by initial sampling, future resampling should be conducted on a different set of sampling areas.

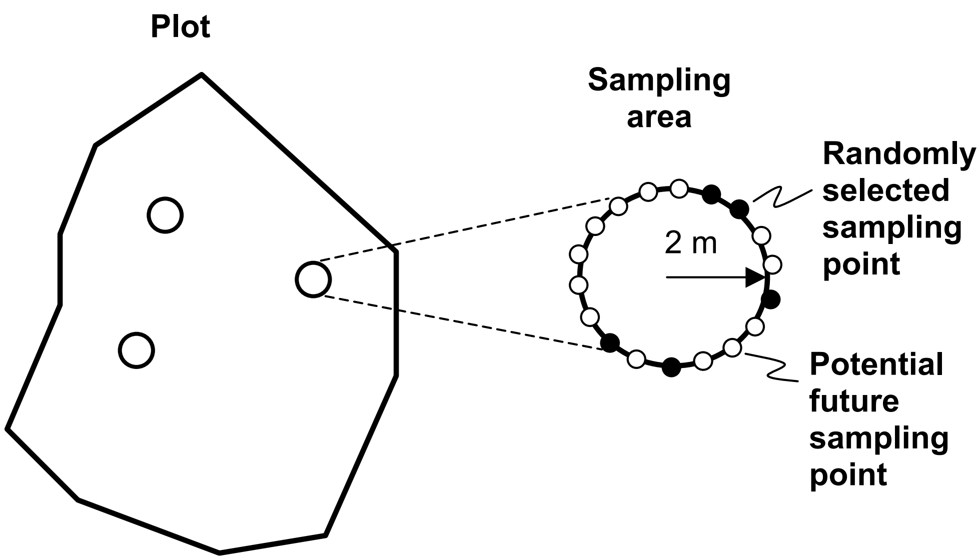

Figure Soil-2. General soil sampling scheme, with multiple sampling areas within a plot, and one or more sampling points per sampling area.

Classical statistical analysis is based on randomly located sampling areas. Conversely, systematic grid-based locations may be more conducive to laying out the plot and geostatistical analysis. The concern with systematic sampling is that there may be an unknown pattern in the plot, e.g. from a previous land use or a future land use, that may bias results should the grid coincide with the pattern. Using randomly located sampling areas is a safer approach.

For a given number of sampling areas per plot (n), the highest statistical power occurs if there are multiple sampling points per sampling area (p). For a given number of total sampling points per plot ($p_{total\ plot}$), the highest statistical power occurs if there is only one sampling point per sampling area. For a situation where both $p_{total\ plot}$ and n are adjustable, rather than given, and the project is constrained by limit funds, the highest statistical power can be attained by

$$p = (\sigma^2_{points}/\sigma^2_{areas})^{0.5}(cost_{area}/cost_{point})^{0.5}$$

where p is the number of sampling points per sampling area, σ^2_{points} is the variance among sampling points within an area, σ^2_{areas} is the variance among areas, and $cost_{area}$ & $cost_{point}$ are the costs per area and per point, respectively. Good estimates of the variances and costs require *substantial* preliminary sampling, which usually is not feasible. From a practical standpoint, if sampling is conducted with machinery that is expensive (time and resources) to move from one sampling area to another within a plot, but is efficient in taking samples at multiple points once it is set up, then multiple sampling points per sampling area are worthwhile. In contrast, if samples are collected by hand, then a single point per sampling area will likely be most cost-effective to produce a high statistical power.

Desired sensitivity and uncertainty

This project address questions about changes in a single plot and differences in change between two plots, where those two plots may have different treatments. The numbers of soil sampling points needed to address these questions depend on the desired levels of sensitivity and uncertainty, and on the variability of soil C among sampling areas within a plot. The variability of soil C within a plot will vary with the cross-sectional area of the sample. Typically, the larger the cross-sectional area, the smaller the variability among sampling points and among sampling areas, because small-scale variability is captured within the sample. However, the quantitative relationship for a given plot can be determined only with intensive sampling of that plot.

The analysis presented here assumed one sampling point per sampling area and resampling of different sets of sampling areas. Sampling more than one point per sampling area and resampling the same sampling areas may or may not decrease the number of sampling areas required, depending on the structure of the spatial variability (e.g. Homann et al. 2008). Further, transforming the variable, soil C, may lead to statistical distributions that are more normal, thereby more closely meeting the assumption of normality and leading to more justifiable results. This analysis used the following desired levels of sensitivity and uncertainty.

Change in soil C in a single plot

sensitivity: detect a real change of 20% of existing soil C

uncertainty: real change = measured change ± 10% of existing soil C

Difference in change in soil C between two plots

sensitivity: detect a real difference in change of 20% of existing soil C

uncertainty: real difference in change

= measured difference in change ± 10% of existing soil C

Number of sampling areas (n) for a single plot

The minimum detectable change for a single plot (MDC_{plot}) is based on a two-sample t-test with equal sample sizes (Zar, 1999), where the two samples represent two sampling times whose sampling points are independent from each other. Alpha = 0.05. Power = 0.8. df = 2n-2

$$MDC_{plot} = s_{plot}(2)^{0.5}(t_{0.05(2),df} + t_{0.2(1),df})$$

where $s_{plot} = s\,(1/n)^{0.5}$ and s is the within-plot sample standard deviation, which is taken as the best estimate of the within-plot population standard deviation, which is assumed to be constant over time; n is number of sampling points at each sampling time; df = 2n-2. The equation can be solved for n, given any desired MDC_{plot} and s. Table Soil-1 shows the n required to conclude there is a change, if a real change of 20% occurred, based on s from several studies.

Merely concluding that there is a real change does not indicate the magnitude of that change. The magnitude and its uncertainty are indicated by (although technically not equivalent to) the 95% CI of the real change.

$$95\% \text{ CI of real change} = \text{measured change} \pm s_{plot}(t_{0.05(2),df=2n-2})$$

The desired 95% CI may be expressed in terms of existing soil C:

95% CI of real change = measured change ± fraction of existing soil C

For example, for a measured change of 20%, and a fraction of existing soil C of 10%,

95% CI of real change = 20% measured change ± 10% of existing soil C
= 10 to 30% of existing soil C

The n required to limit the uncertainty of real change to this level is presented in Table Soil-1.

Table Soil-1. Sample numbers required to detect a minimum change of 20% and 10% of the existing soil carbon content in a single plot at a 95% confidence interval for selected soils in Minnesota. Sample numbers are those required at each sampling interval.

System	Soil depth	Soil C (kgC/m2)	s (% of existing soil C)	sample numbers required to detect 20% change	sample numbers required to detect 10% change
Cedar Creek Abandoned fields[1]	0-10 cm	1.5	18	18	26
	10-30cm	1.6	12	9	13
	30-50cm	1.3	15	13	19
Cedar Creek Forest[1]	O horizon	0.6	31	50	75
	0-10 cm	2.1	18	18	26
	10-30cm	1.7	17	16	24
	30-50cm	1.3	18	18	26
Cedar Creek field 76 [2]	0-10	1.88	36.12	67	93
Western MN[2]					
lowest	0-15	2.0	9.15	6	8
highest	0-15	1.7	42.34	93	150
all groups	0-15	2.1	27.39	42	65
Waseca, MN[3]					
Clarion	0-15	3.1	6.45	4	5
Nicollet	0-15	3.3	3.64	3	3
Webster	0-15	4.0	6.75	4	5
Nemadji State Forest[2]	0-10	4.3	34.33	60	84
	10-25	1.7	26.74	37	52
UMORE Park, Rosemount, MN[2]	0-15	4.17	10.69	7	11

[1]Data from Homann and Grigal, 1966.

[2]Unpublished data, Nater and Brozowski.

[3]Data from Adams, 1984

Number of sampling areas (n) for difference in change between two plots

The minimum detectable difference in change between two plots (MDD_{change}) is based on a two-sample t-test of change. Alpha = 0.05. Power = 0.8.

$$MDD_{change} = s_{change}\,(2)^{0.5}(t_{0.05(2),df} + t_{0.2(1),df})$$

where $s_{change} = s_{plot}(2)^{0.5}$; n is number of sampling points on each plot at each sampling time; df = 4n-4. The equation can be solved for n, given any desired MDD_{change} and s. Table Soil-2 shows the n required to conclude there is difference in a change, if a real difference in change of 20% occurred; for example if one plot changed 10% and the other 30%.

Merely concluding that there is a real difference in change between two plots does not indicate the magnitude of that difference. The magnitude and its uncertainty are indicated by (although technically not equivalent to) the 95% CI of the real difference in change.

95% CI of real difference in change
= measured difference in change ± $s_{change}(t_{0.05(2),df=4n-4})$

The desired 95% CI may be expressed in terms of existing soil C:

95% CI of real change
= measured difference in change ± fraction of existing soil C

For example, for a measured difference in change of 20%, and a fraction of existing soil C of 10%,

95% CI of real difference in change
= 20% measured change ± 10% of existing soil C
= 10 to 30% of existing soil C

The n required to limit the uncertainty difference in change to this level is presented in Table Soil-2.

Table Soil-2. Sample numbers required to detect a minimum change of 20% and 10% of the existing soil carbon content between two plots at a 95% confidence interval for selected soils in Minnesota. Sample numbers are those required at each sampling interval.

System	Soil depth	Soil C (kgC/m2)	s (% of existing soil C)	sample numbers required to detect 20% change	sample numbers required to detect 10% change
Cedar Creek Abandoned fields[1]	0-10 cm	1.5	18	33	50
	10-30cm	1.6	12	16	22
	30-50cm	1.3	15	24	35
Cedar Creek Forest[1]	O horizon	0.6	31	100	148
	0-10 cm	2.1	18	33	50
	10-30cm	1.7	17	31	45
	30-50cm	1.3	18	33	50
Cedar Creek field 76[2]	0-10	1.88	36.12	131	183
Western MN[2]					
lowest	0-15	2.0	9.15	10	14
highest	0-15	1.7	42.34	180	270
all groups	0-15	2.1	27.39	80	120
Waseca, MN[3]					
Clarion	0-15	3.1	6.45	5	7
Nicollet	0-15	3.3	3.64	3	3
Webster	0-15	4.0	6.75	6	8
Nemadji State Forest[2]	0-10	4.3	34.33	119	165
	10-25	1.7	26.74	73	101
UMORE Park, Rosemount, MN[2]	0-15	4.17	10.69	12	17

[1]Data from Homann and Grigal, 1966.

[2]Unpublished data, Nater and Brozowski.

[3]Data from Adams, 1984

Materials

Soils should be sampled to at least a depth of 50 cm, and preferably to the current rooting depth or the anticipated rooting depth under a different management practice. Soils should be sampled by layers designated by depth from the surface of mineral soil. Layers should be at least 10 cm thick, because thinner layers have high uncertainty with respect actual thickness that is sampled.

Soils should be sampled by corers with minimal core compaction or by quantitative soil pits. A large cross-sectional area of the sample is beneficial, because typically, the larger the cross-sectional area, the smaller the variability among sampling points, as the small-scale variability is captured within the sample. However, the quantitative relationship for a given plot can be determined only with intensive sampling of that plot.

Soil organic C (kg/m^2), hereafter call soil C, should be calculated for each individual sampling point (or for each sampling area if multiple sampling points per sampling area are composited prior to chemical analysis):

$$\begin{aligned}\text{soil C (kg/m}^2\text{ per layer)} = {} & \text{C concentration (\% of oven-dried mass) / 100\%} \\ & \times \text{ soil mass (kg oven-dried / sample)} \\ & \div \text{ cross-sectional area of sampler (m}^2\text{ / sample)}\end{aligned}$$

where each variable is measured for each sampling point, and soil is defined as the material within the sample volume that contains C.

An *equivalent* expression is

$$\begin{aligned}\text{soil C (kg/m}^2\text{ per layer)} = {} & \text{C concentration (\% of oven-dried mass) / 100\%} \\ & \times \text{ soil bulk density (g/cm}^3\text{)} \\ & \times \text{ layer depth (cm)} \\ & \times \text{ (1 - \% rock volume/100\%)} \\ & \times \text{ 0.001 kg / g} \times \text{10,000 cm}^2\text{/ m}^2\end{aligned}$$

where

$$\text{soil bulk density (g/cm}^3) = \text{soil mass (kg oven-dried / sample)} \div \text{cross-sectional area of sampler (m}^2 \text{ / sample)} \div \text{layer depth (cm)} \div (1 - \% \text{ rock volume}/100\%) \div 10{,}000 \text{ cm}^2/\text{ m}^2$$

where each variable is measured for each sampling point, and rock is defined as material within the sample volume that is not included in the estimate of soil C. In most cases, this would be what is normally referred to as stones that do not contain C. In some cases, large woody roots would also be excluded and their C (kg/m^2) would be estimated by some other technique.

If soils have significant calcium carbonate concentrations, they will need to be treated with acid prior to analysis of C, otherwise C derived from carbonates could be mistakenly measured as organic C.

For examining change, initial samples should be saved so they can be chemically analyzed along with future samples. If not, actual differences between two samplings may be confounded by differences in analytical techniques and instruments. But the initial samplings must be stored under conditions such that their C concentrations will not change. We recommend air (or mild-oven) drying, followed by freezing (storage at ~ -20° C).

Limitations of the method

Large numbers of sampling areas per plot are required to yield adequate levels of sensitivity and uncertainty (Tables Soil-1 and Soil-2). Resampling the same areas might reduce the number of required sampling areas, but this depends on plot-specific spatial variability (Homann et al. 2008). Relocating sampling areas may be improved by documenting high-precision, high-accuracy GPS coordinates, and by placing a metal marker, e.g. rebar, at depth in the soil.

If the within-plot standard deviation, s, is to be used to determine required numbers of sampling areas (Tables Soil-1 and Soil-2), it needs to be established to relatively high certainty. Unfortunately, this can only be accomplished with a preliminary study that measures a large number of sampling areas on each specific plot.

Soil sampling will disrupt portions of the plot. The magnitude of the disruption will depend on the type of sampling. Exact locations of sampling and spatial extent of disruption should be carefully documented so subsequent sampling does not occur in the disrupted areas.

Longterm storage of samples may be challenging.

Soil sampling and processing may have to be adapted to each plot, because of high coarse fragments that make sampling difficult; coarse woody debris and trees in forests, which prevent sampling soil beneath them; changes in coarse woody debris and trees in forests, which change which areas can and cannot be sampled; C-containing soil aggregates that do not disperse under conventional soil processing procedures (Homann et al. 2004).

Potential sources of error

There may be seasonal cycles in soil C due to root death and decomposition. In forests, there may be seasonal changes in O layer C due to autumnal litterfall and its subsequent decomposition. Sampling at the same time of year would alleviate this potential problem.

Estimates of C concentration, coarse fragments, and bulk density are sometimes taken from different data sets, hence different sampling points, and used to estimate soil C (kg/m^2). This has two potential consequences:

1) biasing soil C values for individual samples, and biasing the average soil C value of several samples at a single point in time – although if the bias is similar at two points in time, the change between the two points in time may be relatively unbiased;

2) creating unknown uncertainty in the soil variability estimates if covariances between the variables are not taken into account.

The initially specified depth defines the lower boundary of the system whose changes we wish to quantify. Unfortunately, the same lower boundary may be difficult to identify in subsequent sampling if there is (i) erosion from the site, (ii) sediment deposition to the site, (iii) movement of soil within the site, and (iv) compaction or expansion of soil due to changes in organic matter or other processes. Under these circumstances, applying the initially specified depth from soil surface to the subsequent sampling depth will define a lower boundary that is different from the initial one, which will influence the evaluation of change in soil C within the system. Similarly, evaluations of change in the individual layers may be influenced. There are three approaches to contending with these processes:

1) For processes (i), (ii), (iii), and (iv), ignore the processes and define the lower boundary at subsequent sampling to be at the initially specified depth from the soil surface. This can create substantial bias if only a surface soil layer (e.g. 0-10 cm) is analyzed, because the 0-10 cm at subsequent sampling does not represent the initial 0-10 cm depth. It creates much less bias if the full profile is analyzed as a single layer, e.g. 0- 100 cm depth. However, analysis of the full profile may be insensitive to significant soil C changes at the soil surface because the uncertainty in full-profile soil C would overshadow those changes.

2) For processes (i), (ii), (iii), and (iv), place an identifiable marker at the lower boundary during the initial sampling. In subsequent samplings, sample to the depth of the marker. Clearly, disturbance and its effect on C is an issue with this approach.

3) For process (iv) only, define the lower boundary by mass of inorganic matter (kg m^{-2}) rather than by depth. This approach assumes that the amount of *in*organic matter in the system is constant, while the organic matter and its C constituent can change. The system may be defined, for example, as the surface 200 kg of inorganic matter m^{-2}. In practice, the soil must be sampled in relatively thin layers (e.g. 5 to 10 cm thick) of known cross-sectional area, mass of inorganic matter is computed – which can be done by subtracting soil organic C and associated organic matter from soil mass – and successively deeper layers or portions of layers are summed until the specified mass of inorganic matter is reached. The amount of C associated with those layers or portions of layers is then summed. The technique has been used for equivalent soil depths of up to 50 cm (Homann and Grigal 1996, Homann et al. 2001, and a slightly less rigorous approach by Ellert et al. 2002). Compared with typical

fixed-depth analysis, the technique requires more layers to be sampled and analyzed because they are thin, and the technique requires more computation. The technique is substantially more challenging in rocky soils, both for sampling and computation.

Potential strengths and weaknesses

The greatest strength is the direct measurement of soil C mass, in contrast to measurement of gas fluxes and their associated uncertainties. There is a physical sample in hand that can be analyzed, and reanalyzed if required. The weakness is the need to preserve samples in an unchanged state so they can be measured concomitantly with samples taken decades in the future.

Large numbers of sampling areas are required. If relatively few sampling areas are measured, there will be little chance of observing change and accurately estimating the magnitude of change.

Procedures of soil sampling can be sufficiently documented so as to be largely repeatable decades later. However, any changes in soil sampling procedures – whether intended or not—may create unknown bias.

Applicable timeframe of measurement

Typically soil sampling is relatively ineffective measuring changes in soil C due to sequestration in timeframes shorter than a decade even for sequestration processes with relatively high rates of C accrual. It is much better suited to measuring differences occurring over decades to centuries.

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