Carbon Sequestration and its Relationship to Forest Management and Biomass Harvesting in Vermont

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Executive Summary

This report explores the issues of carbon storage and carbon sequestration on forestlands. Both storage (the retention of carbon within a "reservoir" such as biomass or soil) and sequestration (the flow of carbon from one reservoir to another) are important aspects of understanding the influence of forest management practices and energy procurement policies on the concentration of carbon dioxide in the atmosphere and, ultimately, global climate change.

In forests, carbon is stored in numerous reservoirs, including living biomass (e.g., trees), standing and dead wood, and (most importantly) soil. Understanding how management and harvesting practices influence the flow of carbon into and out of all of these reservoirs and how they affect the capacity of forests to remove carbon dioxide from the atmosphere in the future is critical to understanding the relationship between carbon sequestration and "carbon neutrality," an oft-cited goal for energy policy. Much credit is currently given to the role of forests in providing fuel that does not enhance global warming, credit that is founded largely on the assumption that biomass is inherently "carbon neutral." However, this assumption is based on the supposition that because forest biomass is ultimately derived from atmospheric carbon (in the molecular form of carbon dioxide, or CO_2) via photosynthesis in the past, then atmospheric carbon derived from forest biomass via combustion will necessarily be taken up again by forests in the future. This assumption is not valid in all cases; carbon sequestration by forests is a function of numerous factors that can be dramatically influenced by management and harvesting actions, including soil erosion, stand age and species composition, fate of woody debris, and soil temperature. Landowners who seek to manage their forestlands to promote carbon sequestration and biomass consumers who seek to be carbon neutral need to consider carefully (a) the conditions required for carbon neutrality to be achieved and (b) directly estimating carbon sequestration.

The focus of this report is preferentially oriented toward two audiences: (1) those who are acquiring forest biomass for energy, specifically Middlebury College, which purchases wood chips for combustion in its biomass plant, and (2) forestland owners who seek to manage their forests for purposes that include carbon sequestration, exemplified in this report by both the members of Vermont Family Forests and Middlebury College. However, our findings and recommendations are not specific to these two groups; any member of these broad audiences – biomass consumers and forestland managers – will find this report relevant.

Measuring carbon sequestration on a plot of land can be accomplished by three different methods, each with their own strengths and weaknesses. (1) Ecological quantification is simple, direct, inexpensive, and standardized but requires long-term monitoring for the preparation of reliable sequestration estimates. (2) Meteorological assessment is limited by technological investment, advanced statistics, and equipment malfunction but examines carbon flux directly and cross-validates other derived sequestration estimates. (3) Computer models are readily available online and provide sequestration estimates without long-term monitoring but are limited by low user-friendliness, high data requirements, and low resolution/precision.

There is potential for each of these methodologies to be applied on lands in western Vermont, but the most accurate estimates of forest carbon sequestration are likely to be calculated through

direct field measurement. We therefore recommended that Middlebury College, because of its stated goal of verifiably achieving carbon neutrality by 2016, establish a long-term ecological quantification program for monitoring its carbon stock. This methodology, while labor intensive, can be implemented cheaply and easily. There are few technological or methodological expenses and there is potential for students to collect the majority of the data – either from classwork or from a paid position. The sampling design and data analysis could easily be performed by the faculty or by a class under direct faculty supervision. The preparation of robust predictions requires long-term measurement, often on the order of ten years, but initial measurements will still be informative. Additionally, the long-term commitment of the College to carbon management virtually demands the establishment of a long-term program. The application of the meteorological method on a few representative plots for validation and verification of the ecological quantification estimates would also strengthen the monitoring program.

Furthermore, the collection of spatially explicit data on stand age and site index on College lands will prepare the College to use an annual carbon storage model specific to the northern hardwood forest, currently under development by the forest carbon research community. Finally, computer models can all be used to validate the estimates of the other methods. A deeper investigation of one of these models (CO2FIX) could prove extraordinarily useful given its successful application in other forest community types. This model allows for experimentation with different management practices and has enormous potential to inform carbon management policy on Middlebury College lands.

Use of these models with data currently available, however, suggests that the college's forestland alone does not have the capacity to sequester the carbon projected to be emitted from the college's biomass plant. Therefore, the assumption that combustion of biomass is carbon neutral depends a great deal on the sequestration capacity of other lands, both the college's non-forest lands (such as agricultural fields and wetlands) and the non-college lands where the biomass was obtained.

Based on a detailed review of the current literature on carbon sequestration in temperate forests, particularly those characteristic of the Middlebury region, we propose the following additions to the biomass procurement standards recommended in the ES 401 report from Fall 2009 and to the Forest Management Checklist (2008) used by Vermont Family Forests:

- ***Promote mixed-species, mixed-age stands***.—These stands tend to have higher carbon uptake and storage because of their higher leaf area. Furthermore, mixed stands include species that are both shade tolerant and intolerant so that there are trees that grow successfully at all levels; this leads to maximum increase in biomass, which enables more carbon sequestration. Finally, mixed stands enable forests to withstand outbreaks of disease and insect infestation so that even if one type of tree succumbs to disease, the other species of trees are able to survive and to continue to sequester carbon. Therefore, landowners should follow these recommendations in order to sequester the maximum amount of carbon in forests.

- ***Protect soils***.—Soils in temperate forests hold about 60% of the total carbon in these forests. In order to maximize the soil carbon stock, adequate soil drainage must be maintained, and soil disturbances must be minimized. Furthermore, soil carbon stocks can be increased by growing species with high net primary productivity so that more nutrients are released back into the soil, which can be stored in the soil for long periods of time. These guidelines are especially important during harvesting, when forest soils are more prone to erosion and water contamination. Great care should be taken to avoid exposing mineral soil, which lies deep in the soil profile and is typically a stable carbon store. Only harvesting practices that protect mineral soils should be used.

- ***Protect wetlands in addition to forests*.—**Histosols are a soil type found in most wetland soils and contain approximately 1170 tons/ha of soil organic carbon. Histosols can contain much more carbon than alfisols and spodosols, the principle soil types of the Champlain Valley and the Green Mountains. Therefore, wetlands and hydric soils of any kind must be protected in order to maintain the soil quality and the capacity to sequester carbon.

- ***Passive management*.**—Management practices for maximum carbon sequestration should emphasize passive management practices. Unmanaged northern hardwoods still sequester more carbon than forests under any active management, and unmanaged forests may continue to sequester carbon for up to 800 years. Even if harvested wood becomes furniture, construction materials, or other long-lived wood products, they still might not store atmospheric carbon as much as previously thought. There has been a 26% increase in carbon from an actively managed forest, even if wood from the forest is put into furniture. Some untested active management practices that mimic natural disturbances could promote new growth in the forest, but until these practices are tested further, we recommend passive management to maximize carbon sequestration in forests.

- ***Maintain high levels of down trees, dead standing timber, and coarse woody debris*.—** While specific numbers of down trees to leave in the forest following harvesting cannot be determined due to the imprecision of the science, harvesting and management practices should maximize the amount of down trees and coarse woody debris left in the forest so that these trees and debris may continue to store carbon.

- ***Leave slash and logging residue behind.*—**Similar to down trees, dead standing timber, and coarse woody debris, slash and logging residue contain carbon. They break down faster into humus, and therefore contribute more carbon to the soil carbon store.

- ***Maintain continuous cover to keep soil temperature low and to keep some litter falling each year.*—**Soil temperature is linearly related to microbial activity; thus, maintaining a lower soil temperature will help to maintain lower rates of soil organic carbon decomposition in the forest, thereby decreasing the amount of carbon released back into the atmosphere. Also, litter needs to continue to fall each year to maintain the amount of carbon that is returning to the soil carbon store from the biotic stores. By maintaining this continuous carbon cycling, more carbon can continue to be stored in the soils of northern hardwood forests.

Much information is still needed to develop a complete understanding of how biomass procurement and management practices affect forest carbon cycles. Better data related to carbon cycles in northern hardwood forests are needed for many different parameters, especially the effects of stand age, site quality, climate change, and soil type. However, despite the value of additional data, the literature, as demonstrated in an annotated bibliography, allows several conclusions that are strong enough on which to make definitive conclusions:

(1) Biomass combustion is not inherently carbon neutral, and many common forest harvesting practices prevent forest stands from re-sequestering the carbon released following harvest and combustion.

(2) To promote carbon sequestration, passive management is superior to active management practices that include harvesting and biomass removal.

(3) For biomass combustion to be carbon neutral, carbon management and accounting must extend to additional lands not associated with harvest and combustion. In other words, to sequester the carbon released through the combustion of biomass harvested from one hectare of forestland over one year, both that hectare as well as additional hectares not associated with the harvest need to be involved. Under currently accepted carbon accounting practices, carbon sequestration on these additional hectares cannot include baseline (i.e., non-additional) carbon sequestration, but only carbon sequestered as a result of additional management actions. Thus, for biomass combustion to be truly carbon neutral, re-forestation of cleared lands and restoration of wetlands needs to be a part of the overall carbon management program.

1. Understanding Carbon

1.1 What is carbon sequestration?

Carbon sequestration refers to the natural and deliberate processes through which carbon dioxide (CO_2) is either removed from the atmosphere or diverted from emission sources and stored in the ocean, terrestrial environments, and geologic formations (Sundquist et al. 2008; Figure 1). Oceans, which mainly store carbon in sediments and dissolved carbonates, are by far the largest global carbon store (Figure 2). Terrestrial carbon sequestration, hereafter referred to in this paper as carbon sequestration, is the process through which CO_2 is absorbed from the atmosphere through photosynthesis and stored in biomass and soils.

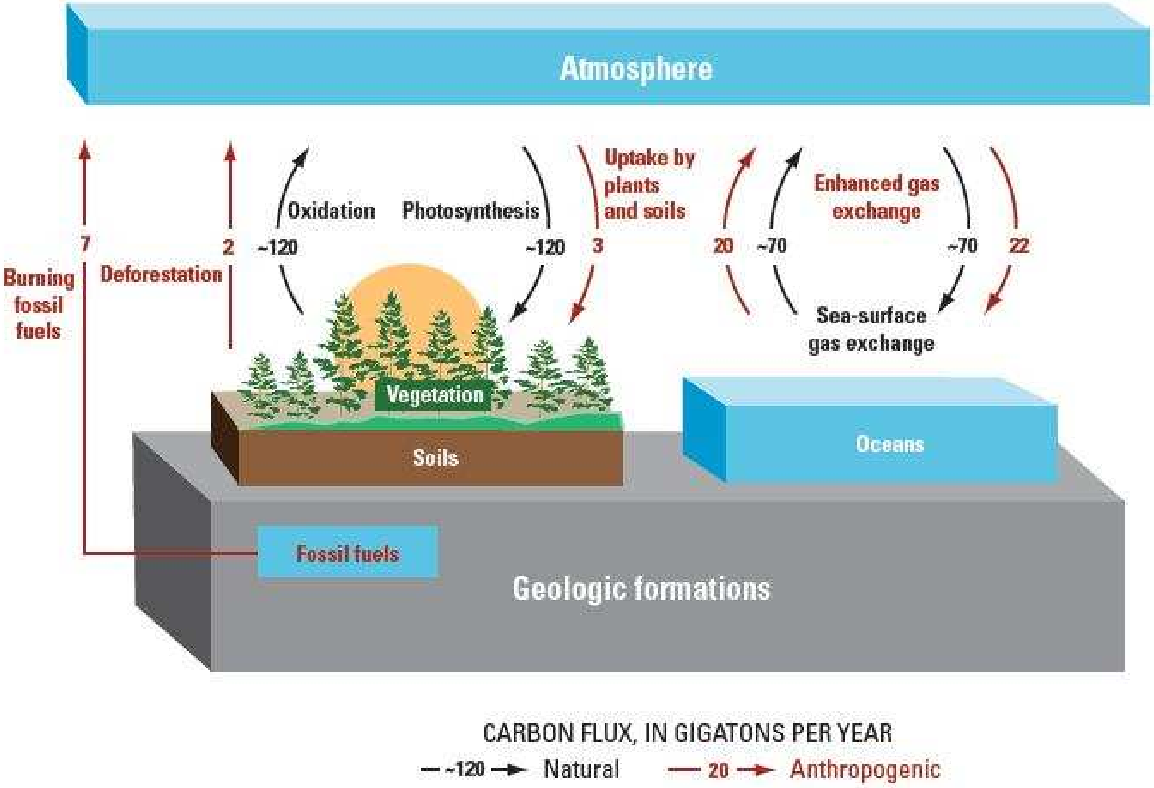


Figure 1. The global carbon cycle. Fluxes shown are approximate for the period 2000-2005, as reported by the IPCC (from Sundquist et al. 2008).

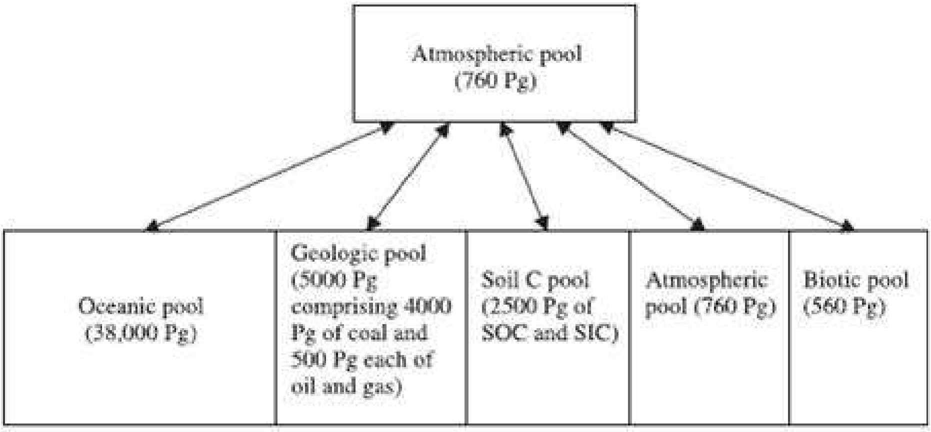


Figure 2. Principal global carbon pools. Soil organic carbon (SOC) and soil inorganic carbon (SIC) are two different forms of carbon that can be stored in the soil (from Lal 2004a).

1.2 What is carbon storage?

Carbon storage refers to the actual amount of carbon contained in plants, soils, oceans, and other non-atmospheric stores. Unlike carbon sequestration, “carbon storage” does not refer to the process or rate of carbon uptake from the atmosphere.

1.3 What is a carbon sink?

A carbon “sink” is a non-atmospheric reservoir that absorbs and stores more carbon than it releases over a long period of time; examples include plants, soils, and oceans. Sinks are sometimes also referred to as carbon stores, reservoirs, or pools, although unlike the term “sink,” these terms do not specify that the carbon reservoir absorbs more carbon than it releases over an indefinite period of time. "Sink" is the opposite of "source," which refers to a carbon reservoir that releases more carbon than it takes up over a given time period.

1.4 What is carbon flux?

Carbon flux refers to the net difference in the exchange of carbon atoms in any molecular form between different reservoirs of carbon. For the forest system, the flux is the exchange of carbon between forests and the atmosphere over a specified period of time, usually reported as one year. A positive flux means net carbon is being sequestered from the atmosphere into forests; a negative flux means net carbon is being emitted from forests (Heath et al. 2003).

1.5 What is biomass?

In ecology, biomass refers to the mass of all living matter present in a given area, including all flora and fauna. It can be measured in a number of ways, including the weight of living tissue or of dried dead tissue. With respect to energy procurement, however, the term biomass is usually restricted to the living and recently dead biological material that can be used for fuel; this definition generally excludes fauna, but includes the trees and woodchips destined for combustion, such as in Middlebury College's biomass plant. Except when noted, this paper uses the second definition.

1.6 What is the carbon cycle in a forest?

The carbon cycle in a forest ecosystem is the flow of carbon between the atmosphere and a series of carbon pools (Figure 3). The main carbon pools in a forest ecosystem are:

- Live trees: diameter at breast height at least 2.5 cm, including all coarse roots, stems, branches, and leaves.
- Standing dead trees: diameter at breast height at least 2.5 cm, consisting of coarse roots, stems, and branches.
- Understory vegetation: shrubs, bushes, and saplings with diameter at breast height less than 2.5 cm, consisting of roots, stems, branches, and leaves.
- Down dead wood: dead wood on the ground over 7.5 cm in diameter, includes stumps and coarse roots of stumps. Down dead wood is also known as coarse woody debris and large woody debris.
- Forest floor: organic material on the ground, includes fine woody debris less than 7.5 cm in diameter, fallen leaves and twigs, humus, and fine roots.
- Soil organic carbon: below the forest floor layer, includes fine roots and all organic carbon mixed in with the soil (Smith et al. 2004).

The soil organic carbon and live tree carbon pools store the majority of the carbon in the forest ecosystems of New England (NEFA 2002).

Carbon enters the forest carbon cycle when plants take carbon dioxide (CO_2) from the atmosphere and turn it into biomass (e.g., complex carbon-based molecules such as carbohydrates) in either the live trees or understory vegetation pools via photosynthesis. The carbon in the live trees pool is stored as wood, leaves, or roots. However, plants also release carbon back into the atmosphere as CO_2 through cellular respiration, which is a series of chemical reactions that converts carbohydrates created during photosynthesis back into CO_2 as the plant uses the energy stored in the carbohydrates.

Carbon can flow from the live trees and understory vegetation pools into the other forest carbon pools through a variety of mechanisms. First, when leaves and twigs fall from the trees, they join the forest floor carbon pool, which refers to the organic matter at various stages of decomposition that lies above the soil. Decomposition of the organic matter in the forest floor pool releases some of the stored carbon back to the atmosphere. After undergoing decomposition, remnant carbon from the organic matter from the forest floor pool becomes incorporated into the soil and is then considered part of the soil organic carbon pool. The soils of a typical forest in Vermont store over 50% of all the carbon in the ecosystem.

When large limbs or entire trees die, the carbon becomes part of either the standing dead trees or down dead wood pool. Similar to the forest floor, these pools release carbon into the atmosphere as wood decomposes. Additionally, remaining carbon from these pools eventually becomes part of the forest floor and soil organic carbon pools. The flow of carbon through the forest ecosystem is a cycle; carbon is continuously being returned to the atmosphere from which it was sequestered while also being sequestered from the atmosphere. In theory, the forest carbon cycle has the potential to be a closed cycle in which all carbon sequestered from the atmosphere into the forest would return directly to the atmosphere from the forest over an extended period of time, often over hundreds of years.

In the present day, however, the carbon cycle in the forest is rarely closed. Carbon leaves the forest in a variety of ways, including harvest of forest products, erosion of soils, and leaching of carbon from soils. When products such as sawtimber are removed from the forest, all of the carbon stored in them is also removed from the forest carbon cycle. In some cases, the harvested wood is burned and the carbon is returned to the atmosphere at a much faster rate than it would have had it been left to the natural decomposition process of the forest ecosystem. Alternatively, when harvested wood is used for building or for making furniture or similar products, some of the carbon is released in processing the wood, and some of the carbon in the wood is stored for a long period of time as a long-lived product instead of being released back into the atmosphere (Harmon et al. 1996).

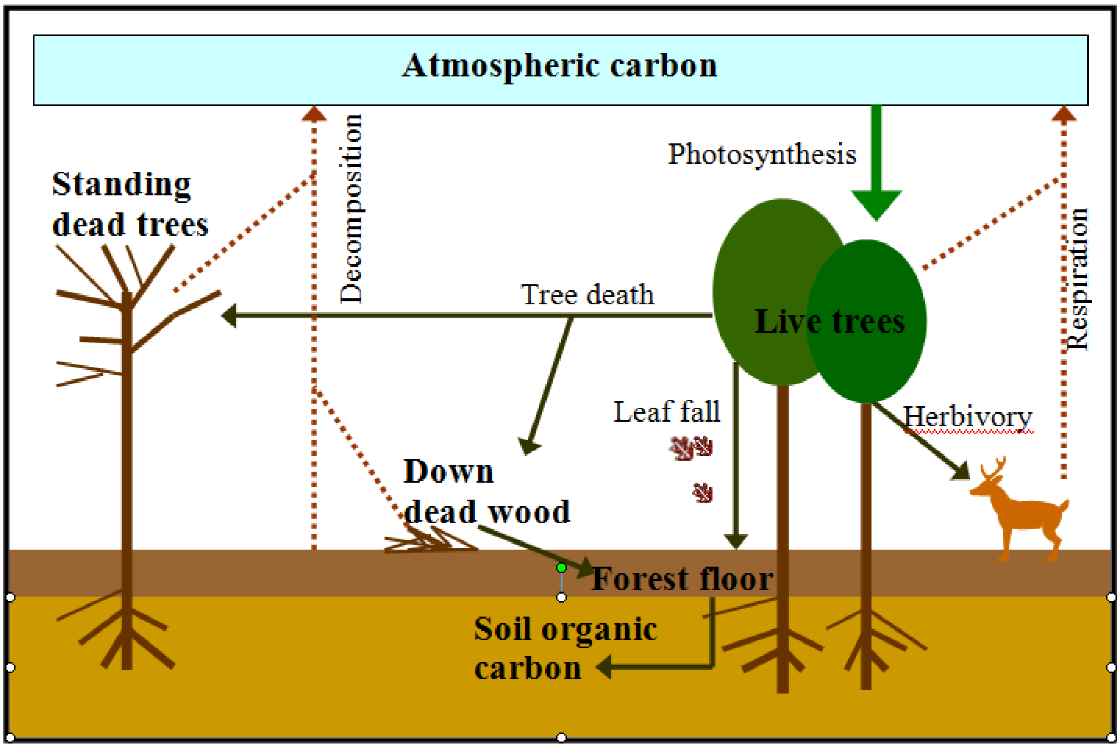


Figure 3. The forest carbon cycle. The terms used are taken from Smith et al. 2004.

1.7 What is carbon neutrality?

Carbon neutrality refers to achieving net zero carbon emissions by balancing a measured amount of carbon released with an equivalent amount sequestered or offset. Middlebury College has committed to achieving carbon neutrality by 2016.

1.8 What are the relationships of carbon sequestration and carbon storage to carbon neutrality and carbon credits?

Carbon sequestration is a fundamental component of achieving carbon neutrality because without increased carbon sequestration, there will continue to be more carbon released into the atmosphere than taken out of it.

Current carbon offsets are only granted for "additionality," which is management that only credits carbon sequestration that is above the current baseline measurements of carbon emissions. Baseline measurements are dependent on the extent of carbon sequestration that naturally happens for a tract of land. Carbon credits are not awarded for land that is already forested. Therefore, companies and countries often turn to harvesting forests using clear-cutting practices in order to receive credits for afforestation following clear-cutting. The manner in which current carbon offsets are accounted has consequences; because no credit is currently given for preserving forestland, the practices that emerge from this accounting policy are not furthering environmentally-friendly efforts towards achieving carbon neutrality through carbon sequestration.

With the current accounting standards, the measurement of carbon sequestration by any institution that seeks to achieve carbon neutrality through biomass burning, including Middlebury College, needs to be examined. There is a debate for the College’s lands, as well as lands worldwide, about whether existing forestland should count towards carbon credits. However, can this carbon really be counted towards calculations of Middlebury College's carbon neutrality? Why should existing management count as sequestration? These questions all relate to the issue of the time frame used for measuring carbon sequestration and whether actions taken in the past should count towards calculating carbon sequestration in the future and, ultimately, whether biomass burning is carbon neutral. Any analysis of biomass procurement standards and its accounting for carbon sequestration must, therefore, look closely at the time scales of biomass harvesting and carbon sequestration.

1.9 Is biomass carbon neutral?

Whether or not burning biomass is carbon neutral depends on the time frame over which sequestration and release of carbon are considered. Many people believe that biomass burning is carbon neutral because it simply returns carbon to the atmosphere from which it was originally sequestered. Middlebury College's biomass facility was designed under the assumption that burning biomass is by definition carbon neutral and is considered a large step toward the goal of the college being carbon neutral by 2016 (Middlebury College 2007). However, the assumption that biomass is inherently carbon neutral is potentially misleading because it does not take into account the ultimate fate of the carbon released by the facility or how that carbon will contribute to future stores of carbon in the atmosphere. Instead, this assumption focuses on the source of carbon in the past and its release in the present. By this same logic, coal and other fossil fuels are also carbon neutral because they contain carbon molecules that, like as for biomass, were derived from atmospheric CO_2 and photosynthesis, albeit hundreds of millions of years ago.

Even when looking toward the future rather than focusing on past sequestration, many people believe that burning biomass is carbon neutral because harvesting biomass is thought to allow other trees left in the forest to increase their growth, thereby sequestering more carbon (Cote 2010). Harvesting, however, often has damaging effects on forests' ability to sequester and store carbon. Therefore, it cannot be assumed that as much carbon as is released by burning biomass will be sequestered by the same forest from which the biomass was harvested. In fact, available data indicate that this is rarely the case.

In order for burning biomass to be truly carbon neutral, the same amount of carbon being released by the burning would needs to be sequestered either on the same land from which the biomass was harvested, or on other land managed to optimize carbon sequestration above its baseline rate. There are two approaches that Middlebury College could take in an effort to make its biomass facility carbon neutral. First, procurement standards for biomass chips could require that land from which wood has been harvested is managed in a way that ensures that as much carbon as is released by burning biomass is also sequestered by the land. Second, the lands the College owns – both forested and unforested – could to be managed in such a manner that they sequester the carbon beyond what they would have sequestered had no additional management actions been taken. Recommendations for management practices that may enable carbon neutrality will be explained throughout this paper and summarized in the concluding section.

2. Why Carbon Sequestration?

2.1 Why should one care about sequestering carbon?

Climate change is one of the most pressing issues in the world today. Human activities, especially the burning of fossil fuels, have caused an increase in the concentration of carbon dioxide (CO_2) in the atmosphere, which is a large contributor to climate change. It is generally thought that one way to reduce our CO_2 emissions will be to reduce our dependency on fossil fuels and use renewable resources like biomass (US Environmental Protection Agency 2006). Carbon sequestration in trees and soil as a means of minimizing atmospheric carbon stores is a concept that had until recently been undervalued as a means to help prevent global climate change. It has been shown, however, that forests and soils have a large influence on atmospheric levels of CO_2. Furthermore, geologic sequestration and ocean sequestration are also effective in CO_2 storage (Figure 4). However, CO_2 emissions from the combustion of fossil fuels are currently greater than the uptake of atmospheric CO_2 into terrestrial and marine sinks; thus, greenhouse gases continue to accumulate in the atmosphere. Carbon sequestration must therefore become a vital part of a comprehensive strategy to offset anthropogenic CO_2 emissions and minimize future climate change (Adams and Post 1999).

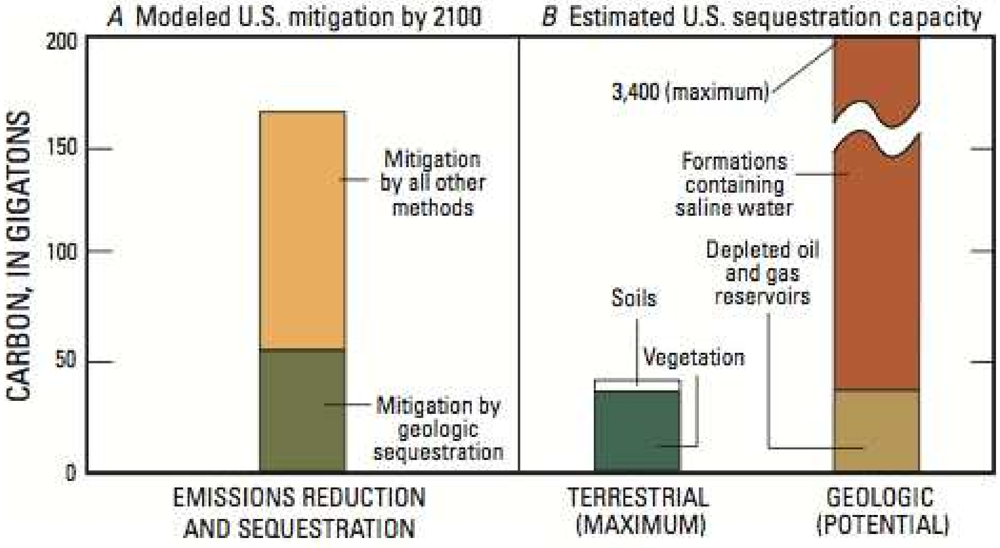


Figure 4. Estimated US atmospheric CO_2 mitigation requirements and potential sequestration capacities (from Sundquist et al. 2008).

The IPCC Assessment Report in 2007 estimated that about 100 billion metric tons of carbon over the next 50 years could be sequestered through forest management, which would offset 10-20% of the world's projected fossil fuel emissions. These models indicate that annual global emissions during the next century need to be reduced by more than 75% in order to stabilize atmospheric CO_2 at about 550 parts per million (Sundquist et al. 2008). For the US, McCarl and

Schneider (2001) suggest that between 50 and 150 million metric tons of additional carbon sequestration per year could be achieved through changes in agricultural soil and forest management.

Enhancing the natural processes that remove CO_2 from the atmosphere is one of the most cost-effective means of reducing atmospheric levels of CO_2, and also reduces dependency on fossil fuels.

2.2 Regardless of whether biomass is or isn't carbon neutral, is it still a better alternative to fossil fuel?

Yes. In theory, it is a renewable carbon source that has the potential to have close to zero net carbon dioxide emissions. This potential, however, depends upon the strategies used to manage the forests where biomass is harvested as well as other, non-harvested lands. It results in lower emissions of methane, sulfate, and hydrocarbons, and requires no dependence on the importation of foreign oil. Fossil fuels are considered non-renewable resources because their replenishment rate is low relative to their consumption rate (Scrase and Watson 2009). Furthermore, biomass is derived directly from photosynthesis, which has the potential to regenerate biomass at a very high rate.

Biomass is a renewable energy source derived from organic matter and includes dead trees, branches, wood chips, bark, sawdust, livestock manure, paper products, and many other resources. Biomass currently generates only about 10% of the primary energy consumed in the world, although that level is significantly higher in developing than in developed countries. Biomass creates about 1/3 the energy than a comparable amount of coal because it is less energetically efficient in its combustion, although this lower efficiency is balanced by its rapid renewability. doesn't deplete a non-renewable fuel. However, currently only about 3% of the US power supply comes from biofuels (Berndes and Hansson 2007).

Unfortunately, using biomass for energy production comes with challenges. The infrastructure for this technology is not abundant and biomass is a more costly fuel than coal and natural gas for electric production. Conversely, it has benefits that coal and natural gas don't have. According to Berndes and Hansson (2007), using biomass reduces greenhouse gas emissions by not adding the materials into landfills. Among the available types of renewable energy, biomass is unique in its ability to provide solid, liquid, and gaseous fuels, which can be stored and transported. The potential source for bioenergy is large, especially in forest-rich nations, in richer countries where there is a surplus of agricultural land. Hall and Scrase (2003) believe that biomass has the potential to become a more important fuel source in the future but that the energy systems adopted to use biomass must demonstrate clear environmental and social benefits relative to alternatives if the potential is to be realized. The effects of biomass as a fuel could potentially be detrimental if harvesting resulted in a net loss of carbon or land management practices decreased the sequestration potential of terrestrial sinks.

According to the Middlebury College Biomass Report (Middlebury College 2004), beyond 2010, the fossil fuel factors governing price, supply, and demand could change dramatically for two reasons. Firstly, the demand for petroleum is growing as the supply is diminishing, and secondly, the supply will likely be exhausted between 2020 and 2030. As the depletion of petroleum beings to drive up oil prices, the world's economy will likely switch rapidly to coal and coal byproducts. After this occurs, the petroleum reserves will become exhausted and cost will rise, so a major realignment of energy suppliers and technologies will take place and the shift to renewable resources will only become more vital. (See Middlebury College [2004] for a more detailed discussion of these points.)

2.3 How much CO_2 is released through combustion of biomass relative to fuel oil?

The net benefit of using biomass depends on the carbon emission rates of the displaced fossil fuels (Figure 5). For example, the net emission reduction of switching from coal to biomass will be greater than that of switching from natural gas to biomass, assuming all other factors such as conversion efficiencies remain unchanged (Waupotitsch et al. 1999). At Middlebury College, the goal is to reduce carbon emissions by 12,500 tons, which represented an estimated 40% of the college's 2006 carbon emissions (Middlebury College 2004). This 12,500 tons of CO_2 is calculated by estimating the amount of Number 6 fuel oil that will not be burned if the college were to use 20,000 tons of woodchips per year – almost 2 million gallons. There are 0.01167 tons of CO_2 equivalents per gallon of Number 6 fuel oil. The amount of CO_2 equivalents in 1,078,000 gallons of burned fuel oil equates to 12,500 tons. The report produced by ES 401 (2009) states that burning 20,000 tons of chips in one year will release 17,000 tons of carbon dioxide. If Middlebury College is looking at emissions released by the plant itself, the college is actually adding 4,500 tons of CO_2 above the fuel baseline. Middlebury's estimate fails to include the CO_2 released by wood chips because "Biomass gasification is carbon neutral because it releases the same amount of CO_2 absorbed by growing plants" (Middlebury College 2004). Thus, the College's calculations of a decrease in carbon emissions is expressly based on the assumption that all of the CO2 released will eventually be re-sequestered in carbon sinks.

Further, this figure does not take into account the carbon that is emitted by extracting, harvesting, processing, or transporting of the fuels, but it is difficult to claim a large reduction in CO_2 emissions due to the switch from oil to wood. Even when these factors are added, the literature reviewed suggests that more carbon will be added into the atmosphere. While biomass will be a cleaner fuel, the numbers suggest that CO_2 will actually be added to the atmosphere. This question at Middlebury is one that should be studied further.

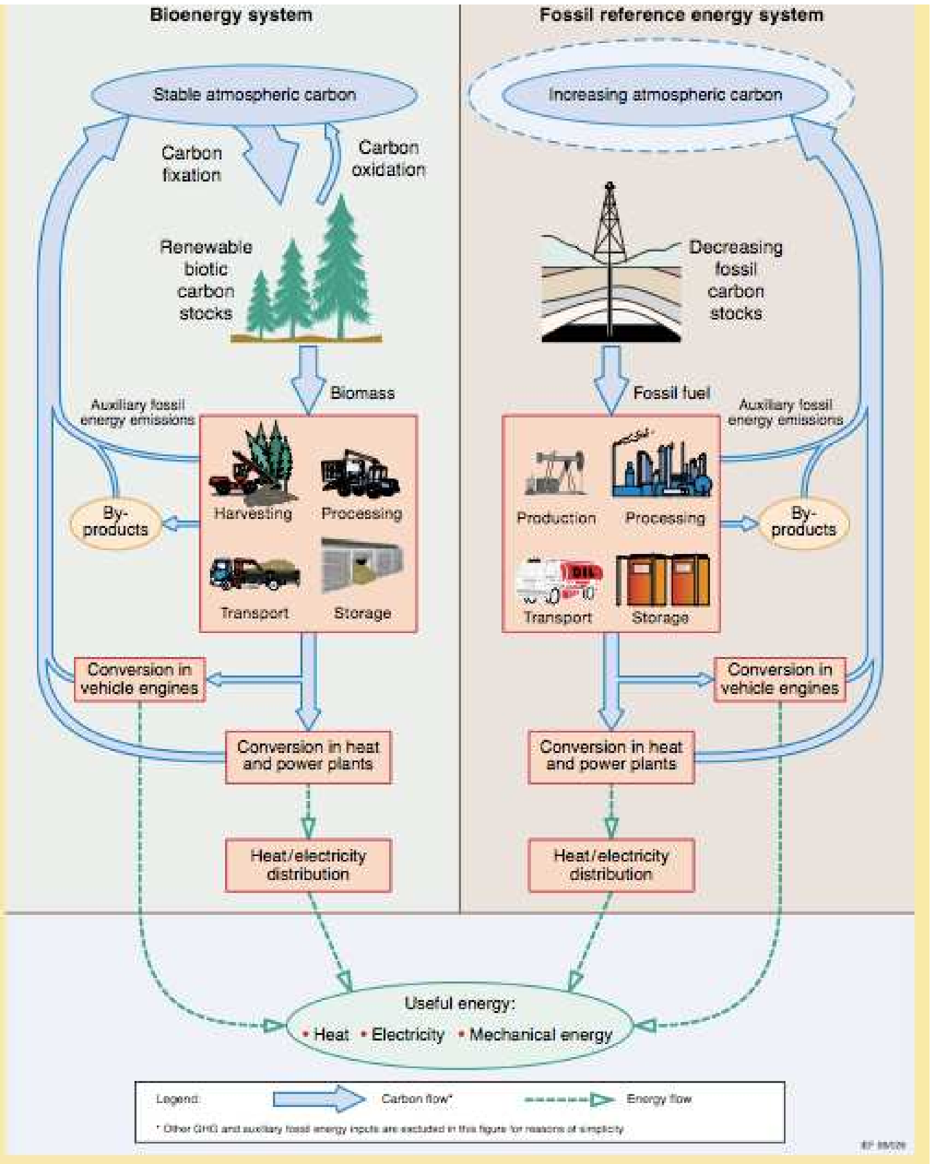


Figure 5. Comparison of bioenergy system and fossil fuel system (from Waupotitsch et al. 1999).

2.4 What standards are already in place to regulate biomass procurement?

Middlebury College's Environmental Studies 401 class of Fall 2009 did a comprehensive study of this. For comprehensive discussion of this question, see the ES 401 (2009).

2.5 What other local organizations should become better informed about carbon sequestration?

All organizations that focus to any extent on forestland management, biomass procurement, or forest health standards should be as well informed as possible about the best available science regarding carbon sequestration. In Vermont, these organizations include Vermont Family

Forests (VFF), Middlebury Area Land Trust (MALT), Cousineau Forest Products, Forest Stewardship Council (FCS), Sustainable Forestry Initiative (SFI), Burlington Electric Department (BED), and the Northern Forest Lands Council.

2.6 What do landowners currently know about carbon sequestration?

While many landowners are aware of what terrestrial carbon sequestration means in theory, they are less aware of what that means in practice. As Josh Phillips, executive director of Middlebury Area Land Trust explained, “I don’t think anyone really understands carbon credits…people don’t have much of a concept of volume or value of carbon sequestration. We live in a place that is populated by extraordinarily educated people, but so many property owners are unaware of carbon sequestration’s importance” (Phillips 2010).

Phillips believes that if people knew more about carbon sequestration, they would be interested in promoting it as an additional management goal. A lot of forest landowners are currently enrolled in management programs and would be interested in adding carbon sequestration in their management practices if it offered monetary value. “Lots of landowners who are in it for the conservation purpose as much as they are for the monetary value would certainly be interested in taking [carbon sequestration] into account” (Phillips 2010). Of the landowners that were interviewed, all of them knew what carbon sequestration was but less than half of them knew how to put it into practice or why it was important.

2.7 What are landowners currently doing in terms of carbon sequestration?

“Other than the college? I don’t think anybody I know is doing anything” (Phillips 2010). Phillips believed that there is more practice in wetland restoration because that is where much of the money for land management currently is. There isn’t as much money in forest restoration, so people are less inclined to plant trees or manage forests if there is not a high monetary value. Phillips believes there are too many considerations to take into account, and people can’t possibly look at sequestration if the data and written explanations aren’t out there. “We are somewhat directed by what money is available…we can only realistically accomplish those [tasks] that have resources given to us” (Phillips 2010). Phillips believes that if there were incentives for carbon sequestration, landowners would do a lot more than they are already doing.

Various VFF landowners interviewed expressed their interest in carbon sequestration but also their skepticism about whether it would bring a monetary income. One landowner explained that he harvested every five to six years for firewood, but nothing more than that. When asked if he would be interested in reading management materials on carbon sequestration if they were available, another landowner/forester replied, “I guess I’d be interested in seeing them but I have a hard time with the concept…people may appreciate the forest for many reasons and if various things become law about what we manage, whether it’s carbon sequestration or something else, it makes things economically difficult…I really don’t know” (Personal communication, kept anonymous by request).

3. Measuring Carbon

3.1 How are carbon storage and sequestration measured on a single plot of land?

3.1.1 Overview

The literature reveals three predominant methods for estimating carbon sequestration on forestlands: (1) ecological quantification, (2) meteorological measurement, and (3) computer models and simulations. There is potential for each methodology to be adopted on Middlebury College land, although there are advantages and disadvantages associated with each procedure. Ecological quantification is simple, direct, inexpensive, and standardized but requires long-term monitoring for the preparation of reliable sequestration estimates. Meteorological assessment is limited by technological investment, advanced statistics, and equipment malfunction but examines carbon flux directly and cross-validates other derived sequestration estimates. Computer models are readily available online and provide sequestration estimates without long-term monitoring but are limited by low user-friendliness, high data requirements, and low resolution/precision. The following section presents these three methodologies as they would ideally be performed and proposes a hybrid methodology designed to meet the College's needs.

3.1.2 Ecological Quantification

<u>Overview</u>.—A series of carbon sequestration measurement guidelines were prepared by Pearson et al. (2007) as a reference for the development of forest carbon inventory and monitoring systems. The guidelines prescribe techniques based on commonly accepted principles of forest inventory, soil sampling, and ecological survey to measure and monitor terrestrial carbon pools. Carbon sequestration, under this methodology, is represented as the net change in forest carbon stock over a designated period of time. The following steps, according to these authors, are therefore necessary to produce credible and transparent estimates of forestland carbon sequestration:

1. Sampling Design – Delineation and stratification of project area; determination of number, type, size, shape, and layout of sample plots.
2. Monitoring Plan – Determination of project duration and sampling frequency; selection of the carbon pools to be measured, monitored, and analyzed.
3. Measurement and Data Analysis – Measurement of living aboveground biomass, living belowground biomass, dead organic matter, and soil organic carbon; data analysis.
4. Estimating Net Change and Uncertainty – Calculation of net change in carbon stock over a designated time period (carbon sequestration); calculation of uncertainty.

These guidelines were designed for use by professionals with a knowledge of sampling, statistical estimation, and forest measurement, but with proper instruction these guidelines could be implemented by students in biology or environmental studies. Additionally, these guidelines are consistent with the accounting standards of the US Department of Energy 1605(b) voluntary reporting registry and provide a methodology for documenting and validating the carbon offset potential of forest management initiatives. The accessibility and standardization of this methodology makes it particularly appropriate for College use.

Delineation and Stratification of Land Area.—Development of the sampling design broadly requires the delineation of boundaries, the stratification of land area, the appropriation of sampling plots, and the determination of project duration and sampling frequency. The spatial boundaries of the pertinent land area must be clearly defined in order to facilitate accurate measuring, monitoring, accounting, and verification. These boundaries can be identified and delineated using permanent boundary markers, clearly defined topographic descriptions, and/or spatially explicit digital documentation, e.g., GPS or GIS. The collection and collation of spatially explicit soil, vegetation, and topographic data associated with the delineated land area is necessary for the division (stratification) of the land area into relatively homogenous units (strata); these divisions facilitate fieldwork and increase the accuracy and precision of measuring and monitoring efforts. The necessary datasets are readily available as GIS data layers (e.g., STATSGO soil maps, USGS Digital Elevation Model (DEM), 1992 National Land Cover map) that can be overlain in a GIS for the identification of strata. The key to stratification is to ensure that measurements are more alike within each stratum than in the sample frame as a whole.

Number, Type, Size, and Layout of Plots.—The number of sample plots within each stratum is determined according to the level of precision demanded by the landowner. Sample sizes are determined for each stratum on the basis of the estimated variance in the carbon stock within the stratum and the proportional area of the stratum. The variance in the carbon stock is either estimated from existing data, such as a forest inventory in a similar area or from preliminary field measurements within a representative area. The methodology for collecting these preliminary measurements is described below. The simplest methodology for calculating the number of required plots uses the following equation:

$$n = \left(\frac{ts}{E}\right)^2$$

In this equation, *E* is the allowable error, calculated by multiplying the mean carbon stock by the desired precision, i.e., mean carbon stock * 0.1 for 10% precision; *t* is the sample statistic from the t-distribution for the 95-percent confidence level; and *s* is the standard deviation of the mean carbon stock. This equation returns the minimum number of plots necessary to meet the desired precision level, but it is generally advisable for this minimum sample size to be increased by at least 10% to accommodate for unforeseen circumstances. There are more complicated statistical analyses available for sample size determination, but the details of these analyses are beyond the scope of this report, and the reader should refer to Pearson et al. (2007) for more information.

Permanent, temporary, and prism sampling plots have all been used for the ecological quantification of carbon sequestration. The trees within a permanent sampling plot are tagged so as to monitor the growth of survivors, the mortality of the initial population, and the growth of new trees. Permanent sampling plots promote scientific accuracy, statistical efficiency, and transparent verification but are vulnerable to the confounding influence of disturbance. Temporary sampling plots, established once per sampling effort, are more tolerant of disturbance and more cost effective but sacrifice precision as a result of reduced covariance. Prism plots, the primary alternative to fixed-area sampling plots, assess carbon storage by measuring the trees close enough to completely fill a predefined sighting angle (prism), a technique known as point sampling. The primary advantage of point sampling is the speed at which data are collected (i.e., no fixed-boundary is involved) but point sampling preferentially samples larger trees and this bias is associated with significant error. It is recommended that the College adopt permanent sampling plots in its carbon monitoring as a means of maximizing both precision and convenience.

Permanent plots locations can be selected randomly or systematically within a stratum; however, if some portions of the stratum have a higher carbon content than others, systematic selection generally results in greater precision than random selection. It is therefore prudent to systematically distribute sample plots according to anticipated patterns in forest carbon sequestration. The size and shape of the distributed sample plots also contribute to the accuracy, precision, and time/cost of forest carbon measurement. Although larger plots require more time and effort, increasing plot area reduces variability between plots, allowing for a smaller sample size while achieving the same precision level. There is a strong preference in the literature for nested fixed-area circular sample plots in the ecological quantification of carbon stocks (Figure 6). A nested plot design increases efficiency and accuracy when different sized trees occur in different densities within the forest. The optimum area for nested plots can be anticipated by predicting changes in stem density and mean stem diameter over time or by direct measurements of proxy stands of a known age. The literature also encourages the subdivision of sample plots according to the measured carbon pool. For example, although all trees should be measured within an entire plot, data on nontree vegetation, litter, and soil only needs to be collected within smaller subplots.

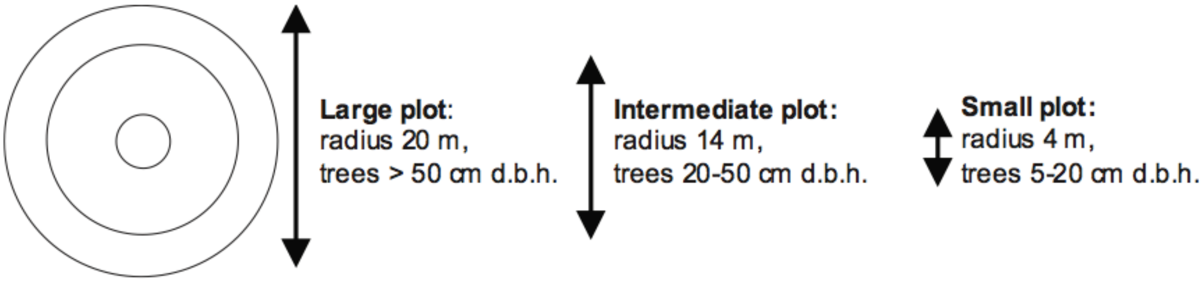
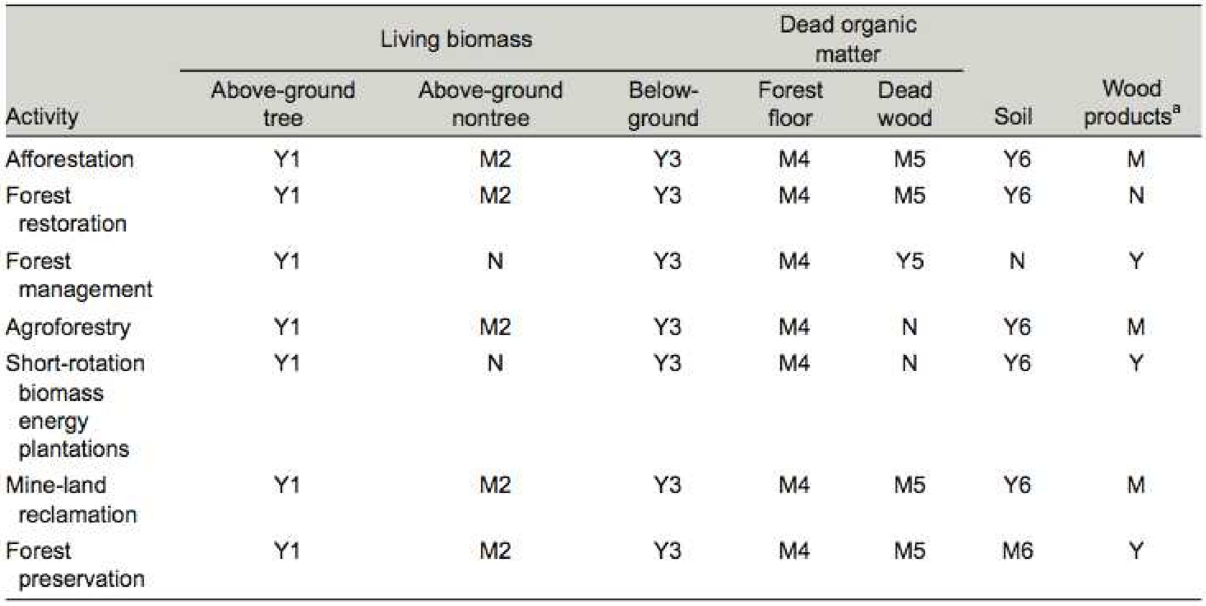


Figure 6. Schematic of nested fixed area circular sample plots with suggested radius and diameter limits. The radius and diameter limits for each circular plot would be a function of local conditions and expected size of the trees through time (from Pearson et al. 2007).

Measuring and monitoring only the most critical carbon pools can further reduce data collection requirements. The identification of critical pools depends on several factors, including expected rate of change, magnitude and direction of the change, availability and accuracy of methods used to quantify change, and cost of measurement. The 1605(b) process includes a *de minimis* criterion whereby any emission that is equal to or less than 3 percent of the total need not be monitored. Moreover, it is generally not cost effective to monitor pools that are expected to change by a small amount relative to the overall rate of change (e.g., understory herbaceous vegetation in the case of afforestation). These decisions should be made according to the needs and resources of the user but general guidelines are available for reference (Table 1). The measurement of above- and belowground living tree biomass is generally required for all activity types, whereas the necessity of measuring the other carbon pools varies according to activity type. It is important for these decisions to be made wisely and the user should refer to Pearson et al. (2007) for more details.

Table 1. A decision matrix illustrating the importance of measuring and monitoring carbon pools within each forest activity type. Y = Yes: the change in this pool is likely to change and the change should be monitored; N = No: the change in this pool will be small to none and it not necessary to monitor this pool; M = Maybe: the change in the pool might require measurement depending on forest type and/or management intensity (from Pearson et al. 2007).

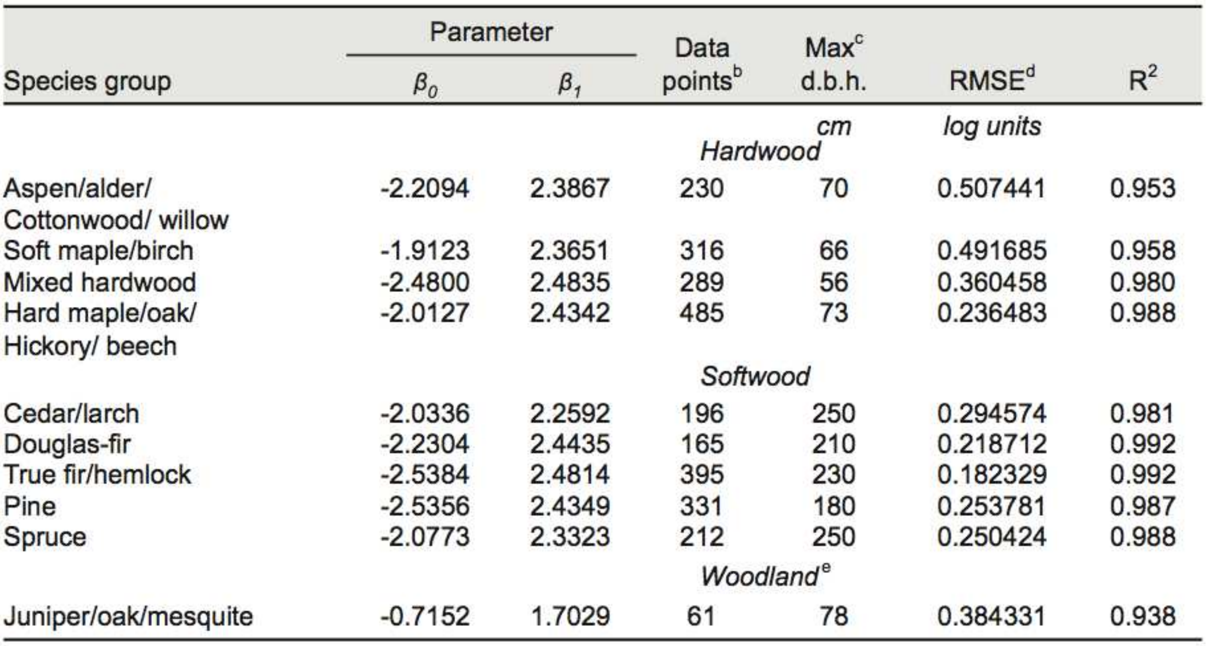


	Living biomass			Dead organic matter			
Activity	Above-ground tree	Above-ground nontree	Below-ground	Forest floor	Dead wood	Soil	Wood products[a]
Afforestation	Y1	M2	Y3	M4	M5	Y6	M
Forest restoration	Y1	M2	Y3	M4	M5	Y6	N
Forest management	Y1	N	Y3	M4	Y5	N	Y
Agroforestry	Y1	M2	Y3	M4	N	Y6	M
Short-rotation biomass energy plantations	Y1	N	Y3	M4	N	Y6	Y
Mine-land reclamation	Y1	M2	Y3	M4	M5	Y6	M
Forest preservation	Y1	M2	Y3	M4	M5	M6	Y

Duration and Frequency of Monitoring.—The frequency of monitoring is directly related to the rate and magnitude of the expected change. This becomes a cost-benefit analysis so that the frequency of monitoring should be determined by the magnitude of the expected change; for example, it is unnecessary and cost-ineffective to frequently monitor forests with slow rates of change. The literature suggests a sampling frequency of approximately 5 years assuming average forest process dynamics. For carbon pools that respond more slowly, such as soil, even longer periods can be used – perhaps 20 years between sampling events. The frequency of monitoring should thus be defined in accordance with the rate of change of the carbon stock and with appropriate consideration of disturbance risk. The effects of natural disturbances cannot be captured with widely spaced monitoring intervals. The potential for disturbance must therefore be considered when determining the frequency of monitoring.

Measurement of Living Aboveground Biomass.—The carbon stocks of trees are estimated most accurately and precisely by direct methods such as a field inventory, where all the trees above a minimum diameter are measured within a sample plot. The suggested minimum diameter differs amongst community types but a dbh ≥ 5 cm is the recommended benchmark for the northern hardwood forests. Biomass and carbon stock are estimated from the application of appropriate allometric equations to these tree measurements. Biomass equations are often reported for individual species or groups of species, but the literature is still incomplete for all US tree species; however, recent analyses have shown that equations based on multi-species groups work well for US forests (Schroeder et al. 1997; Jenkins et al. 2004). Jenkins et al. (2004) compiled all available diameter-based allometric regression equations for estimating total aboveground and component biomass. More than 1700 biomass equations were assembled for more than 100 species from 177 sources. The generalized equations, many of which are applicable to Middlebury College lands, are shown in Table 2 below.

Table 2. Parameters and equations for estimating total aboveground biomass for hardwood and softwood species grouped into ten classes. The generalized equation is of the form $y = e\text{^}[\beta_0 + \beta_1 \ln(x)]$ *where y is the total aboveground biomass (kg) for trees 2.5 cm and larger in dbh and x is the dbh (from Pearson et al. 2007).*



Species group	Parameter β_0	β_1	Data points[b]	Max[c] d.b.h.	RMSE[d]	R^2
				cm	*log units*	
			Hardwood			
Aspen/alder/ Cottonwood/ willow	-2.2094	2.3867	230	70	0.507441	0.953
Soft maple/birch	-1.9123	2.3651	316	66	0.491685	0.958
Mixed hardwood	-2.4800	2.4835	289	56	0.360458	0.980
Hard maple/oak/ Hickory/ beech	-2.0127	2.4342	485	73	0.236483	0.988
			Softwood			
Cedar/larch	-2.0336	2.2592	196	250	0.294574	0.981
Douglas-fir	-2.2304	2.4435	165	210	0.218712	0.992
True fir/hemlock	-2.5384	2.4814	395	230	0.182329	0.992
Pine	-2.5356	2.4349	331	180	0.253781	0.987
Spruce	-2.0773	2.3323	212	250	0.250424	0.988
			Woodland[e]			
Juniper/oak/mesquite	-0.7152	1.7029	61	78	0.384331	0.938

The carbon stock of nontree vegetation can be measured by simple harvesting techniques in small subplots (about two per tree plot are recommended) for each sample plot. The herbaceous plants within a 0.25 m^2 frame are removed to ground level, pooled by plot to give a composite sample, oven-dried, and weighed. This harvest methodology is not always practical with large under understory shrubs so an alternative approach is to develop biomass regression equations for local shrubs based on variables such as crown area and height, diameter at base of plant, or number of stems on a multi-stemmed shrub; however, this approach is ambitious and may not be practical for the average inventory.

Measurement of Belowground Biomass.—The measurement of belowground biomass (coarse and fine roots) is time consuming, laborious, and often destructive – it is simply more efficient to apply a regression model to estimate belowground biomass (living and dead) as a function of above ground biomass. The following regression model can be used to estimate belowground biomass in the temperate region:

$$BGB = e^{-1.0587 + 0.8836 * ln(AGB) + 0.2840}$$

Where BGB = belowground biomass density in tons per hectare (t/ha) and ABG = aboveground biomass density (t/ha). The correct use of this equation is important when calculating the increase in carbon in belowground biomass. For tagged trees in permanent plots, it is not possible to simply calculate the total aboveground biomass at Time 1 and Time 2, apply the equations, and then divide by the number of years. This approach does not account for ingrowth or mortality of trees. Instead, change in belowground biomass carbon stocks should be calculated by the following method:

1. Calculate aboveground biomass at *Time 1* using allometric equations and appropriate expansion factors.
2. Calculate increment of biomass accumulation above ground between *Time 1* and *Time 2* and add to *Time 1* to estimate the biomass stock at *Time 2.*
3. Apply the appropriate equation to estimate belowground biomass at each time interval.
4. Calculate the annual change in stock of biomass below ground as *(Time 2 Belowground - Time 1 Belowground) / Number of Years).*

Measurement of Dead Organic Matter.—The measurement of the carbon stock of dead organic matter requires an examination of the forest floor, dead down wood, and dead standing wood. The forest floor is sampled using simple harvesting techniques within 0.25 m^2 subplots within the larger permanent plot. All live vegetation from the sample area is removed carefully with a pair of clippers and the entire volume (surface layer to mineral soil layer) of the underlying forest floor is removed from the sampling frame. All litter within the sample frame is collected and pooled with the other sample. A well-mixed subsample is used to determine oven-dry-to-wet mass ratios to convert the total wet mass to oven-dry mass. The biomass per unit area can then be calculated from the equation:

$$(\text{forest-floor oven-dry weight (g)} / \text{sampling frame area (cm}^2)) * 100$$

Where multiplying by 100 converts the units to tons per hectare and multiplying by an additional 0.5 gives the amount of carbon (t/ha).

A time-efficient method for sampling down dead wood is the line-intersect method. A 100-m transect line is run through the center of the plot and the diameters of all the downed debris intersecting the line are measured for diameter and density class (sound, intermediate, and rotten). The volume of wood per unit area is calculated for each density class as:

$$Volume\ (m^3/ha) = \pi^2 * [(d1^2 + d2^2 ....dn^2) / 8L]$$

In this equation, $d1, d2, dn$ = diameter (cm) of each of the n pieces intersecting the line, and L = the length of the line. The common methodology for determining density in the field is to strike the wood with a strong sharp blade. If the blade bounces off, it is sound, if it enters slightly, it is intermediate, and if the wood falls apart, it is rotten. Samples of dead wood in each class are collected to determine density. The mass of the dead wood is then calculated as the product of the volume per density class and the wood density for that class.

Standing dead wood can be measured as part of the living tree inventory but a different series of measurement and observations must be recorded. For example, if the standing dead tree contains branches and twigs and resembles a live tree (except for leaves), this observation should be indicated in the field notes. The amount of biomass can then be estimated using the appropriate biomass regression equation with a slight subtraction, around 2-3%, for the missing leaves. Similarly, a dead tree exhibiting only a few branches must be classified in proportion to its original size so adequate reductions in biomass can be estimated. The volume of a standing dead tree with no branches can be estimated from measurements of the basal diameter and height as well as an estimate of its top diameter. The biomass of all standing dead trees must also be reduced according to the observed density class using the same calculations described in the passage above.

Measurement of Soil Organic Carbon.—The measurement of soil carbon stock requires the examination of soil depth, soil bulk density, and soil organic carbon concentration within both the mineral and organic soil layers. A detailed description of the methodology used to assess forest soil carbon stock is found in Lal et al. (2001) and Robertson et al. (1999). The general methodology requires the clearing of the forest floor to expose the soil layer and coring of the soil layer to maximum depth. The soil depth is calculated from identification and measurement of soil layers within the core. The bulk density is determined by calculating the oven-dry weight of a known volume of sampled soil. The soil carbon concentration can be determined via direct assessment using the dry combustion method (Amacher et al. 2003), the dichromate oxidation method (Nelson and Sommers 1996), or the pressure calcimeter method (Sherrod et al. 2002). The details of these three methods are beyond the scope of this report but interested readers should refer to the cited literature. Following the calculation of these three variables, the amount of carbon per unit area can be calculated using the following formula:

$$C\ (t/ha) = [(soil\ bulk\ density\ (g/cm3) * soil\ depth\ (cm) * \%\ C] * 100$$

In this equation, %C must be expressed as a decimal fraction; for example, 2.2% C is expressed as 0.022.

3.1.3 Meteorological Measurement

The meteorological measurement of annual forest carbon storage monitors changes in carbon fluxes above the forest canopy and provides an integrated measure of net ecosystem carbon uptake or loss that represents the sum of individual carbon fluxes occurring within the ecosystem. The cumulative net exchange of carbon between forest and atmosphere over one year is the meteorological estimate of annual forest carbon storage and should, on principle, be identical to an annual carbon storage estimate prepared by an ecological quantification in the same forested area. Meteorological methods for estimating annual forest carbon storage require continuous, high-frequency (10 per second) measurements of three-dimensional wind speed and CO_2 concentrations above the forest canopy using a sonic anemometer and infrared gas analyzer respectively (Gough et al. 2008). The eddy-covariance statistical method is generally the preferred method of estimating forest carbon fluxes from wind and CO_2 data although the details of this statistical method are beyond the scope of this report (Gough et al. 2008; Baldocchi 2003; Schmid et al. 2003).

The height placement of these instruments determines the size of the area contributing to the monitored carbon fluxes – a range anywhere from several hectares to many square kilometers. The area of monitored forest, known as the carbon flux footprint, also varies with weather conditions as wind speed affects the distance CO_2 travels before being sampled by instruments on the meteorological tower. Additionally, harsh weather conditions, especially heavy rain and wind, cause gaps in the otherwise continuous measurements of wind speed and CO_2 concentrations. These conditions compromise the integrity of the gathered data as data gaps must be filled through carbon flux simulations (Hollinger and Richardson 2005). The spatial heterogeneity of the carbon flux footprint may also be a substantial source of uncertainty when meteorological methods are applied to patchy landscapes encompassing different plant functional and structural types (Oren et al. 2006). Similarly, the measurement of carbon fluxes over complex terrain is unreliable because CO_2 can enter and exit these systems below the forest canopy where the instruments are placed. Although carbon fluxes are measured with high uncertainty, close long-term agreement between ecological and meteorological estimates of annual carbon storage provides important cross-validation of these independently derived estimates.

3.1.4 Computer Models and Simulations

Overview.—The carbon storage and sequestration potentials of forestlands can be estimated according to several different mathematical models. These models are readily available online and provide carbon sequestration estimates without long-term modeling; however, mathematical models are often limited by low user-friendliness, high data requirements, and low resolution/precision. The methodology and applicability of the following models are discussed in the passages below:

1. Carbon Density Model (Heath et al. 2003).
2. Site Index and Stand Age Model (Gough et al. 2008).
3. CO2FIX Model (Masera et al. 2003).
4. Other Carbon Models (COLE, FIA, CCT, VFS).

Although these models vary widely in complexity and specificity, they all provide a useful estimation of local to regional forest carbon storage and sequestration. The accuracy of these estimates increases with the resolution and completeness of the inputted data, but informative predictive ranges can be constructed from even limited datasets. There is potential for each of these models to inform College forest management policy and the disadvantages and advantages of each are discussed below.

Carbon Density Model.—The simplest methodology for estimating carbon storage in forestlands uses the carbon densities of the major eastern forest types to generate regional carbon storage estimates (Heath et al. 2003). This model suggests that the carbon storage potential of a uniform forest is the product of the associated carbon density and forest acreage as shown in the following equation:

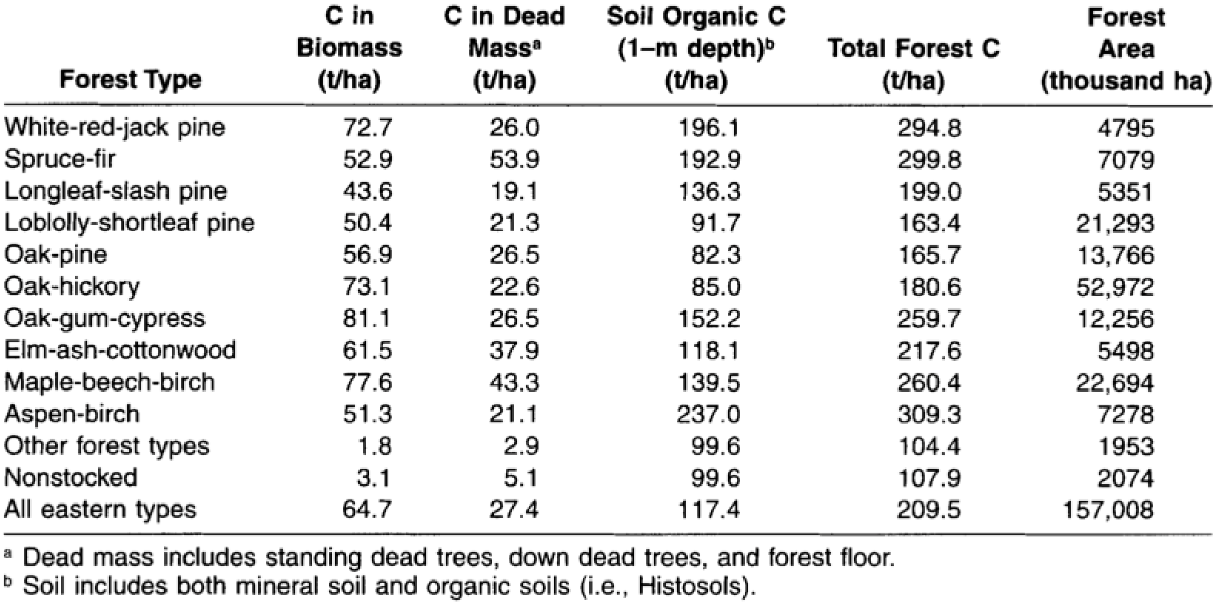
*Carbon Store (ton) = Carbon Density (ton/hectare) * Forest Area (hectare)*

The carbon storage potential of a mixed forest would therefore be the sum of the carbon stores of the contributing forest types as shown in the following equation:

$$Carbon\ Store = \sum (Carbon\ Density)_i * (Forest\ Area)_i$$

The carbon densities of the primary northern hardwood forest types – maple-beech-birch, oak-hickory, spruce-fir, and white-red-jack pine – are reported in Heath et al. (2003) as the sum of the carbon densities of the living biomass, dead biomass, and soil organic matter within each forest community (Table 3). The ideal application of this methodology requires spatially explicit forest type data combined with the appropriate carbon density values, but these data are often unavailable. The classification of forestland as coniferous, deciduous, or mixed, a feasible achievement given the widespread availability of data on land cover/land use (LULC), allows for rough calculations of carbon storage potential by assigning best-fit carbon densities to these forest types. We used this methodology for Middlebury College land, described in greater detail below.

Table 3. The carbon densities (t/ha) within the standing biomass, dead biomass, and soil organic matter in each of the major eastern forest types (from Heath et al. 2003).



Forest Type	C in Biomass (t/ha)	C in Dead Mass[a] (t/ha)	Soil Organic C (1–m depth)[b] (t/ha)	Total Forest C (t/ha)	Forest Area (thousand ha)
White-red-jack pine	72.7	26.0	196.1	294.8	4795
Spruce-fir	52.9	53.9	192.9	299.8	7079
Longleaf-slash pine	43.6	19.1	136.3	199.0	5351
Loblolly-shortleaf pine	50.4	21.3	91.7	163.4	21,293
Oak-pine	56.9	26.5	82.3	165.7	13,766
Oak-hickory	73.1	22.6	85.0	180.6	52,972
Oak-gum-cypress	81.1	26.5	152.2	259.7	12,256
Elm-ash-cottonwood	61.5	37.9	118.1	217.6	5498
Maple-beech-birch	77.6	43.3	139.5	260.4	22,694
Aspen-birch	51.3	21.1	237.0	309.3	7278
Other forest types	1.8	2.9	99.6	104.4	1953
Nonstocked	3.1	5.1	99.6	107.9	2074
All eastern types	64.7	27.4	117.4	209.5	157,008

[a] Dead mass includes standing dead trees, down dead trees, and forest floor.

[b] Soil includes both mineral soil and organic soils (i.e., Histosols).

Site Index and Stage Age Model.—There are several different methodologies for estimating the carbon sequestration potential of forestland – all ranging in simplicity, practicality, and accuracy. The simplest methodology utilizes a predictive model for evaluating forest carbon sequestration potential based on successional status (forest age) and integrated site productivity (site index)

(Figure 7; Gough et al. 2008). The model, developed within the aspen-dominated forests of northern Michigan, uses the following equation to calculate annual forest carbon storage:

$$\textit{Annual Carbon Storage (t/yr)} = 0.4336 * e^{0.0143 * [\ln(\textit{Stand Age}) * (\textit{Site Index})]} * \textit{Area (ha)}$$

Site index and stand age are routinely measured by foresters and regional data is available from the USDA Forest Inventory and Analysis Program (FIA). Although the FIA site index and stand age data is reliable on the regional scale, field measurement of site index and stand age yield better estimates of local carbon sequestration.

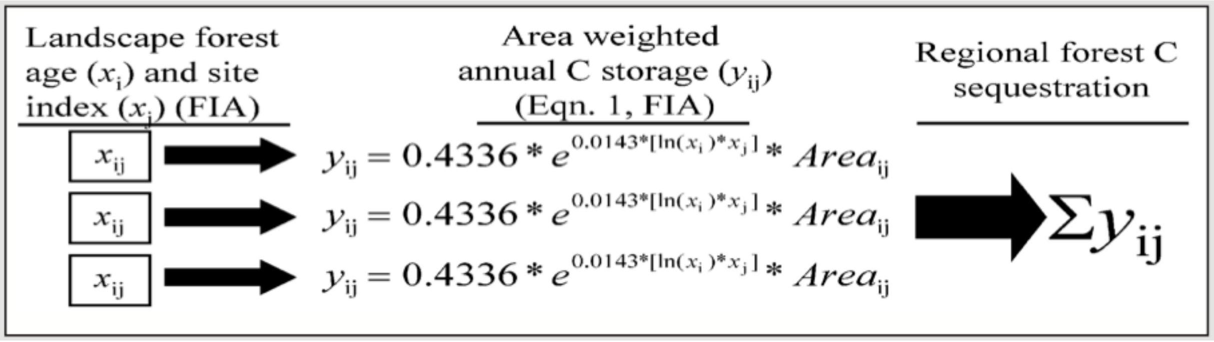


Figure 7. A predictive model for evaluating the forest carbon sequestration potential based on successional status (forest age) and integrated site productivity (site index) within the aspen dominated forests of northern Michigan (Gough et al. 2008).

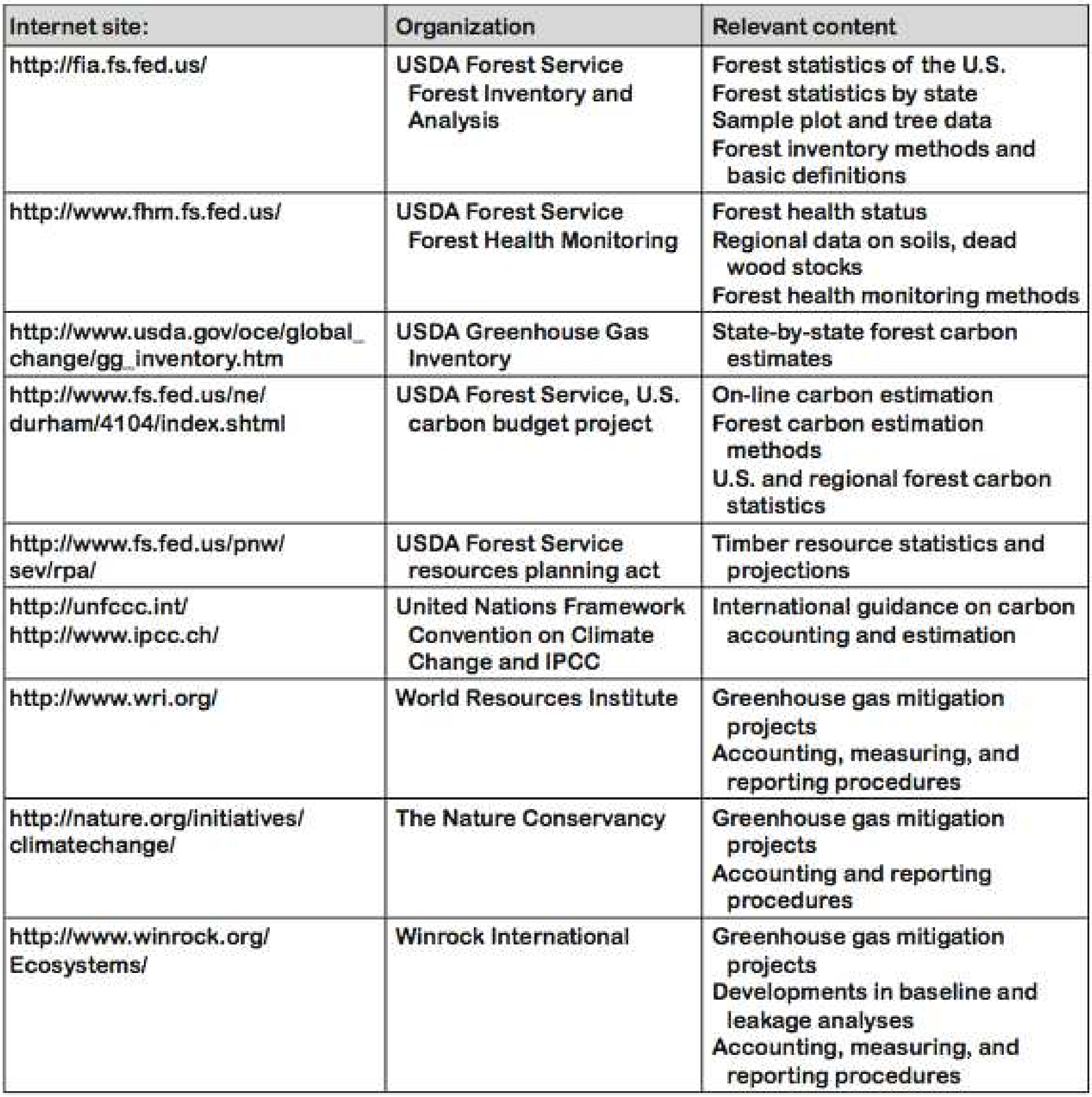
Site index, a measurement commonly used to describe site productivity, is the average height of the dominant and codominant trees of a base age within a forest site. The heights and ages of the dominant and codominant trees within a forest site are collected using a clinometer and increment borer respectively. These values are aligned along the appropriate species-specific site index curve for the determination of the site index value. The forest stand age is determined either from knowledge of forest growth history or from a reconstruction of age class distribution via tree coring and ring counting. The equation calculated by Gough et al. (2008) based on the aspen-dominated forests of Michigan is not applicable to the northern hardwood forest; however, the development of an applicable equation is on the horizon and measurements of site index and stand age on College lands should be made in preparation for its release (Christopher Gough, Virginia Commonwealth University, personal communication, 21 January 2010).

<u>CO2FIX Model</u>.—The CO2FIX Model, a user-friendly tool for dynamically estimating the carbon sequestration potential of forest management, agroforestry, and afforestation projects, has received significant attention in the literature (Masera et al. 2003). CO2FIX is a multi-cohort ecosystem-level model based on carbon accounting of forest stands, including forest biomass, soils, and products. Carbon stored in living biomass is estimated with a forest cohort model that allows for competition, natural mortality, logging, and mortality due to logging damage. Soil carbon is modeled using five stock pools, three for litter and two for humus. The dynamics of carbon stored in wood products is simulated with a set of pools for short-, medium- and long-lived products and considers processing efficiency, re-use of by-products, recycling, and disposal forms. Additionally, the CO2FIX V.2 model can estimate total carbon balance of alternative

management regimes in both even- and uneven-aged forests, and thus has a wide applicability for both temperate and tropical conditions. The geographical and managerial flexibility of the model encourages its application to Middlebury College lands and management plans. More investigation is necessary to determine the data requirements but the model uniquely offers the ability to experiment with management plans to maximize forest carbon sequestration.

Other Carbon Models.—There are a number of other carbon models available online that are designed for a regional examination of carbon storage and sequestration. The Carbon OnLine Estimator (COLE), for instance, is an online tool used to generate carbon estimates based on forest inventory data for any area of the country all the way to the county level. The model estimates carbon "growth and yield" curves explicitly for 1605(b) greenhouse gas reporting, thereby demonstrating its importance as a verification tool in both present and future calculations of carbon storage and sequestration potential. The US Forest Carbon Calculation Tool (CCT), the predecessor to COLE, uses publicly available data collected by the USDA Forest Service's Forest Inventory and Analysis Program (FIA) to generate state-level annualized estimate of carbon stocks on forestland based on FORCARB2 estimators. A carbon reporting function has recently been integrated into the Forest Vegetation Simulator to examine the carbon impacts of any simulated management, including prescribed fire, thinning, or salvage logging. The model tracks above- and belowground live tree biomass, above- and belowground dead tree biomass, down dead wood, forest floor, and herbs and shrubs using calculation methods consistent with US carbon accounting rules and guidelines. The Forest Service has also published an economic model to help foresters, managers, and project developer work with private forest landowners to assess the economic profitability of participating in carbon markets. This model, known as CVal, provides a discounted cash flow analysis based on a full accounting of variables, including tract size, carbon sequestration rate, carbon price, and enrollment and trading costs. The model was developed to evaluate managed forest and afforestation projects traded on the Chicago Climate Exchange, but its methodology could be adapted for other trading programs. A number of other models readily available online are listed below (Table 4). There is potential for all these models to verify and validate estimates of carbon sequestration on College land and to inform new forest management policy.

Table 4. The address, organization, and purpose of readily available online carbon storage and sequestration models (from Pearson et al. 2007).



Internet site:	Organization	Relevant content
http://fia.fs.fed.us/	USDA Forest Service Forest Inventory and Analysis	Forest statistics of the U.S. Forest statistics by state Sample plot and tree data Forest inventory methods and basic definitions
http://www.fhm.fs.fed.us/	USDA Forest Service Forest Health Monitoring	Forest health status Regional data on soils, dead wood stocks Forest health monitoring methods
http://www.usda.gov/oce/global_change/gg_inventory.htm	USDA Greenhouse Gas Inventory	State-by-state forest carbon estimates
http://www.fs.fed.us/ne/durham/4104/index.shtml	USDA Forest Service, U.S. carbon budget project	On-line carbon estimation Forest carbon estimation methods U.S. and regional forest carbon statistics
http://www.fs.fed.us/pnw/sev/rpa/	USDA Forest Service resources planning act	Timber resource statistics and projections
http://unfccc.int/ http://www.ipcc.ch/	United Nations Framework Convention on Climate Change and IPCC	International guidance on carbon accounting and estimation
http://www.wri.org/	World Resources Institute	Greenhouse gas mitigation projects Accounting, measuring, and reporting procedures
http://nature.org/initiatives/climatechange/	The Nature Conservancy	Greenhouse gas mitigation projects Accounting and reporting procedures
http://www.winrock.org/Ecosystems/	Winrock International	Greenhouse gas mitigation projects Developments in baseline and leakage analyses Accounting, measuring, and reporting procedures

3.1.5 Recommendations

There is potential for each of these methodologies to be applied on Middlebury College lands but the most accurate estimates of forest carbon sequestration are likely to be calculated through direct field measurement. We therefore recommended that the College establish a long-term ecological quantification program for monitoring its carbon stock. This methodology, while notably labor intensive, can be implemented cheaply and easily. There are few technological or methodological expenses and there is potential for students to collect the majority of the data – either from classwork or from a paid position. The sampling design and data analysis could easily be performed by the faculty or by a class under direct faculty supervision. The preparation of robust predictions requires long-term measurement, often on the order of ten years, but initial measurements will still be informative. Additionally, the long-term commitment of the College to carbon management demands the establishment of a long-term program. The application of the meteorological method on a few representative plots for validation and verification of the ecological quantification estimates would also be enormously helpful.

Furthermore, the collection of spatially explicit data on stand age and site index on College lands will allow cross-validation using the Gough et al. (2008) model and will prepare the College for the coming of an annual carbon storage model specific to the northern hardwood forest. Finally, the computer models discussed above can all be used to validate the estimates of the other methods. A deeper investigation of the CO2FIX model could prove extraordinarily useful given its successful application in other forest community types. This model allows for experimentation with different management practices and has enormous potential to inform carbon management policy on Middlebury College lands.

3.2 How much carbon is currently being stored on college forestlands?

At present it is impossible to calculate the exact amount of carbon that is currently being stored on Middlebury College forestland. While a substantial amount of information exists in terms of land use and land cover on college lands, this information is not specific enough to allow for precise calculations. For example, the college does not have information on age-structure or tree density on its forestland. In addition, existing literature only describes carbon density in broad forest types, like spruce-fir or maple-beech-birch, and not on a site specific basis.

The information that is currently available is quite generalized, but it can be used to estimate the total carbon storage on Middlebury College forestlands. We calculated the total hectares of deciduous, coniferous, and mixed forests types with existing GIS data (Figures 8 and 9) and used in conjunction with forest carbon density data given in Heath et al. (2003). Heath et al. (2003) classify 13 different forest types (e.g., white-red-jack pine, spruce-fir) and include both the carbon densities (tons per hectare, or t/ha) found in the entire forest ecosystem and the amount contained specifically in biomass, dead mass, and soil.

None of the forest types listed in Heath et al. (2003) are identical to the college's forests. Professor Marc Lapin (Program in Environmental Studies, Middlebury College) suggests that the following assumptions can be made:

- Coniferous forests below 1000 feet (304.8 meters) could be best described as “White-red-jack pine.”
- Coniferous forests above 1000 feet (304.8 meters) could be best described as “Spruce-fir.”
- Deciduous forests at any elevation could be best described as predominantly “Maple-beech-birch” with some limited amount of “oak-hickory.”

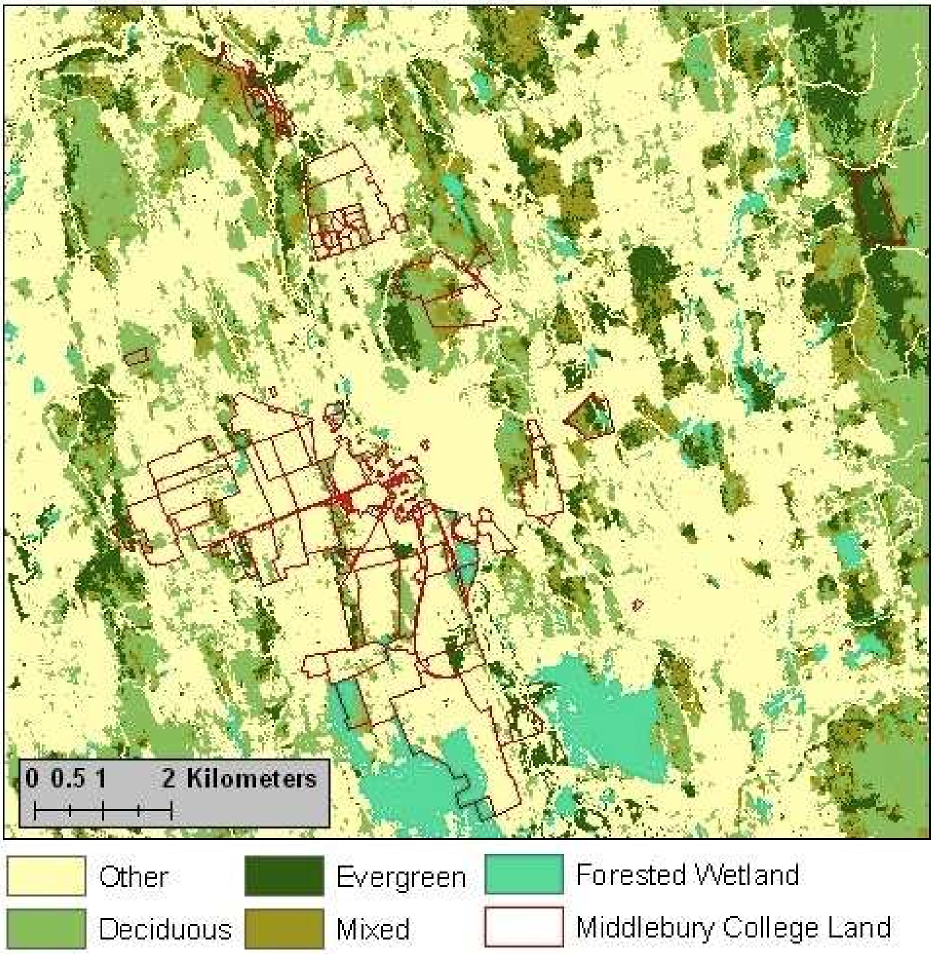


Figure 8. The distribution of forest types on land owned by Middlebury College in Middlebury, Vermont.

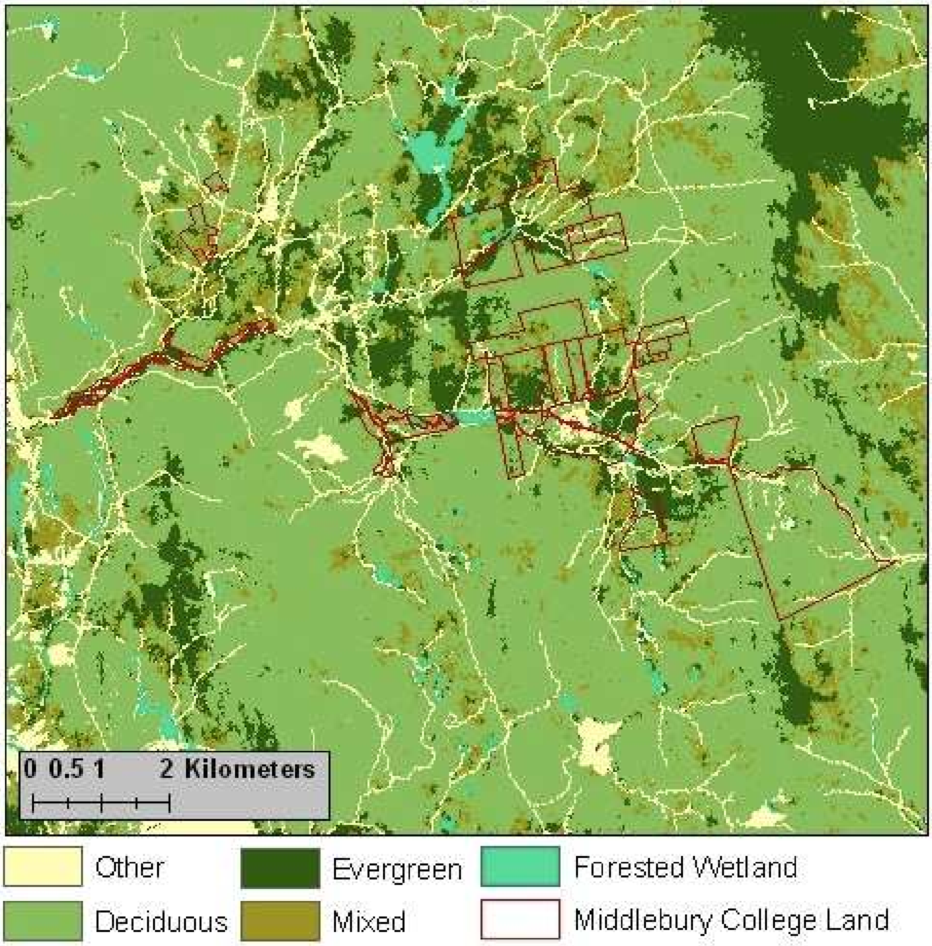


Figure 9. The distribution of forest types on land owned by Middlebury College in Ripton, Vermont.

Using different combinations of forest types, we calculated a range of estimates for the amount of carbon we believe is being stored on the college's forestlands. We multiplied the total forest carbon figures from Heath et al. (2003) by the total hectares of each forest type and found that, based on our best estimates, between 322,923 and 354,129 tons of carbon are currently stored on Middlebury College forestland. Clearly, this range is an estimate and the figures could increase or decrease as variables like forest age structure or soil type change. In addition, this estimate is simply an approximation in the sense that the forest types presented in Heath et al. (2003) do not perfectly match all of the forest types on Middlebury College lands.

The upper range of the estimate was calculated by assuming that all coniferous forest was spruce-fir, all deciduous was maple-beech-birch, and the mixed forest was an average of the total carbon storage of both spruce-fir and maple-beech-birch. This scenario assumes that all deciduous forests are maple-beech-birch. In reality, some of the college's deciduous forests could be more appropriately characterized as oak-hickory, which stores significantly less carbon than maple-beech-birch forests (Table 5).

Table 5. High estimate of total carbon stored on Middlebury College forestland.

Forest Type	**Forest Classification**	**Total Forest Carbon Storage (t/ha)**	**Total Hectares on college lands**
Deciduous	Maple-beech-birch	260.4	726
Coniferous	Spruce-fir	299.8	261
Mixed	Average of maple-beech-birch and spruce-fir	280.1	310

Our low estimate was calculated by assuming that college forestlands contain some oak-hickory (Table 6). Professor Matt Landis (Department of Biology, Middlebury College) estimated that the college's deciduous forests were roughly 20-40% oak-hickory. Thus, the low-range estimate was calculated assuming that the college's deciduous forests were 40% oak-hickory and 60% maple-beech-birch. All coniferous forest was considered to be white-red-jack pine, which has a slightly lower carbon storage capacity than spruce-fir. Oak-hickory and white-red-jack pine figures were averaged to estimate carbon storage potential for the mixed forest.

Table 6. Low estimate of total carbon stored on Middlebury College forestland.

Forest Type	Forest Classification	Total Forest Carbon Storage (t/ha)	Total Hectares on college lands
Deciduous	40% oak-hickory 60% maple-beech-birch	180.6 260.4	290.4 435.6
Coniferous	White-red-jack pine	294.8	261
Mixed	Average of oak-hickory and white-red-jack pine	237.7	310

It is important to note that this range was calculated based purely on the college's forestland. Much of the college's land is agricultural land or wetland, both of which are important for the college's overall carbon budget but are currently not associated with discussions of biomass procurement apart from the potential that the college may in the future convert some of its agricultural land into willow plantations. Our estimate does not take into account carbon stored on forested wetlands or agricultural land because neither of these land-use types could be harvested for biomass. The college does own 141 hectares of forested wetland but information that would allow us to model carbon storage in these regions is unavailable. However, it is important to note that of the 141 hectares of forested wetland, roughly 36 hectares contain histosol soils, which store approximately 10 times more carbon than other soil types found in the region (Lal 2004a; Peter Ryan, Middlebury College, personal communication).

Data presented by Lal (2004a) indicate that histosols contain 1170 tons of organic carbon per hectare, more than any other soil types. Other soil types around Middlebury store less than 200 tons per hectare. Most of the agricultural lands in the Champlain Valley are alfisols, which store only 125 tons per hectare and most of the soils in the Green Mountains are spodosols, which store only 191 tons per hectare (Lal 2004a). This information allows us to estimate that 42,120 tons of carbon are stored within the 36 hectares of histosol soils on college lands (36 hectares of histosol soil * 1170 tons of carbon per hectare). This estimate ignores carbon that could be stored in biomass. This estimate does, however, illustrate the importance of histosols in terms of carbon storage on Middlebury College lands.

The estimated range provides a rough approximation of how much carbon is currently stored on Middlebury College's forestland. Such an estimate is a prerequisite for estimating carbon sequestration, since all such methods define sequestration as "change in carbon storage." Further, an understanding of carbon sequestration on college forestlands is critical to an appreciation of how important it is that carbon sequestration be understood on non-college lands from which biomass is harvested. If college forestlands have the potential to sequester all of the CO_2 emitted from combustion of wood chips at the college regardless of where the chips come from, then the college could potential develop a methodology for monitoring its progress toward achieving carbon neutrality without attention to non-college lands. On the other hand, if college lands are not able to sequester the CO_2 emitted from its biomass plant, then carbon monitoring on those lands is essential.

3.3 Is there potential for Middlebury's forestland to sequester the carbon released by the biomass plant?

Currently, it is unclear whether or not there is potential for the college's forestland to sequester as much carbon as is released by the biomass facility each year. It is unclear because it is not known (a) how much carbon the facility releases each year, or (b) how much carbon is being sequestered annually on college lands. Furthermore, no mechanisms are in place to correct these deficiencies. However, rough estimates can be made for both the amount of carbon emitted annually from the biomass facility and the amount of carbon sequestered annually on college forestlands.

Jack Byrne (Director of Sustainability Coordination, Middlebury College) has made rough initial estimates of carbon emissions from the biomass facility based on data from the 2008-2009 academic year.

Between January and June 2009, during the initial start-up phase of the biomass facility, the college burned 3883 tons of woodchips (Jack Byrne, personal communication). Assuming that the average carbon content of the woodchips was 50%, Byrne used the following information to calculate the amount of carbon released between January and June 2009: Amount of woodchips (3883 tons); Carbon fraction (by weight) of the wood chips (0.5); Conversion factor for carbon dioxide to carbon (44/12); and Conversion factor for completeness of combustion (1, which assumes complete combustion of woodchips).

Using data from Jack Byrne, this results in the following estimate of carbon released between January and June 2009:

$$3883 * 0.50 * (44/12) * 1 = 7119 \text{ tons}$$

Clearly, the 3883 tons of woodchips used in the equation are a drastic underestimate of the amount of chips that the college would use over the course of an entire year. The figure does not include woodchips that would be burned between July and December and it was gathered during the first months of the facilities use when the plant was still being tested and the engineers were still learning how to operate it most efficiently. In addition, equipment failures kept the plant offline for longer than the regularly scheduled maintenance periods, leading to a further reduction in the amount of woodchips burned.

Thus, to say that the biomass plant will emit roughly 7119 tons of carbon each year is a gross underestimate. In order to find a more reasonable figure it is necessary to determine how many tons of biomass the college expects to burn each year when the facility is no longer in the testing phase but is functioning at full capacity. According to the Middlebury College biomass website, the best estimate is 20,000 tons of woodchips. Jack Byrne indicates that it is unlikely the college will reach 20,000 tons this year largely because of extended maintenance periods during which the plant was not functioning. However, our current best estimate is that, when the plant is running at full capacity, the college will burn around 20,000 tons of woodchips.

Thus, a more realistic estimate of carbon emissions is:

$$20{,}000 * 0.50 * (44/12) * 1 = 36{,}667 \text{ tons of carbon}$$

To calculate a rough estimate of the amount of carbon actively sequestered each year by Middlebury College forestland, we utilized an equation developed by Gough et al. (2008) to measure carbon sequestration in the aspen dominated forests of Michigan. The following information was used in the equation:

- forest stand age
- forest site index
- area of forest type

Annual Carbon Storage in tons (net change in carbon stock over a year) is calculated as:

$$0.4436 * e^{[0.143 * \ln(\text{stand age}) * \text{site index}]} * \text{area}$$

The college currently does not have plots from which to collect the necessary data; therefore, Mark Lapin provided estimates for stand age and David Bryne provided estimates for site index. The information presented in Table 7 was used to calculate the annual carbon storage (tons/year) for the college's deciduous, coniferous, and mixed forestland.

Table 7. Annual carbon storage for Middlebury College forestland.

Forest Type	MC Land Area (ha)	Stand Age (yr)	Site Index	Annual C Storage per Hectare (t/ha/year)	Total Annual C Storage (t/yr)
Deciduous	725	70	50	9.04	6556.50
Coniferous	261	70	40	4.93	1285.66
Mixed	309	70	45	6.67	2062.38
Total	**1295**	**70**	**NA**	**NA**	**9904.54**

Based on the equation used, we estimate that Middlebury College's forestland will sequester approximately 9905 tons of carbon annually. We expect that this is an overestimate of annual carbon storage as the coefficient used (0.4436) is, according to Mr. Gough, specific to the aspen forests of Northern Michigan. Aspen grows substantially more quickly than the maple-beech-birch forests of Vermont and this rapid growth enhances their ability to sequester carbon (Gough et al. 2008). Thus, we expect that the coefficient for Vermont forests would be much lower, thereby decreasing our estimate. In addition, lower stand ages and site indices result in a lower carbon storage value and the stand ages and site indices we used are both likely overestimates.

Based on our estimates of both the biomass facility's annual carbon emissions and the ability of the college forestland ability to sequester carbon, it is clear that the college forestland is not sequestering nearly as much carbon as is projected will be emitted by the plant. Even though this is only a rough estimate, the likelihood that a more specific estimate of sequestration is even lower does not bode well for our assumption that the biomass plant is carbon neutral. Such an assumption clearly depends on carbon sequestration on the non-college lands from which the biomass is obtained, discussed in greater detail in the ES 401 Fall 2009 report.

4. Managing Carbon

4.1 What type of forest community sequesters the most carbon?

For cold temperate environments similar to the forests near Middlebury, Vermont, the type of forest that sequesters the most carbon is maple-beech-birch forest. This is based on the total forest carbon (t/ha) in the four main types of northern hardwood forests: maple-beech-birch forest, northern hardwoods talus woodland, hemlock forest, and floodplain forest (Klyza and Trombulak 1999). These carbon densities are based on calculations in forests of the eastern United States in 1997, on timberland only (Heath et al. 2003).

For analyzing types of forests, one can divide forests into mixed stands and single-species stands, and old, new, and mixed-age forests. Forest communities of mixed-species and mixed-age are believed to be the best overall for carbon sequestration. There may be potential to sequester or store additional carbon in complex stand structures with mixed species compositions or several age classes due to complimentary resource use or facilitative improvement in nutrition (Kelty 2006). Mixed-species, mixed-age stands tend to have higher capacity for carbon uptake and storage because of their higher leaf area. Because younger trees have a greater carbon sequestration rate while older trees have greater carbon storage, mixed-age stands are best to capitalize on the different rates of carbon sequestration and different uptakes (Vogt et al. 2007). In addition, mixed stands have greater carbon content than just evergreen or just deciduous forests (Vogt et al. 2007). Temperate evergreens have a higher level of forest carbon and soil carbon when compared to temperate deciduous forests, which could mean that temperate evergreens have greater carbon storage (Lal 2003). However, net rates of carbon uptake by broadleaf trees are commonly greater than those of conifers (Malmsheimer et al. 2008). Therefore, both deciduous and evergreen forest types are needed in order to sequester and store the maximum amount of carbon.

Shade tolerance is also an important characteristic to consider when analyzing carbon sequestration ability of tree species. Shade-tolerant species have greater leaf area, higher stand densities, and grow more wood, and as a result are able to sequester more carbon than shade-intolerant species (Malmsheimer et al. 2008). However, a forest has several levels of growth, and shade intolerant species must occupy the overcanopy. Therefore, a mixed-stand forest would maximize the growth available with the different sunlight conditions for the different levels of forest (Malmsheimer et al. 2008).

4.2 How does soil contribute to carbon sequestration and storage?

The global soil carbon pool, composed of both organic and inorganic carbon, is approximately three times the size of the atmospheric pool and four times the size of the biotic pool (Lal 2004b; Rastogi et al. 2002). Soils are generally acknowledged as the largest store of terrestrial carbon that can be further increased by proper land management practices, particularly on agricultural and forest lands (Amundson 2001). At present, as a result of land use, soil carbon is a source of atmospheric CO_2 in the tropics and possibly a sink in northern latitudes (Amundson 2001). The soil carbon pool has been estimated to compose around 60% of the total carbon stored in temperate forests (Dixon et al. 1994; Figure 10). Accumulation of carbon in the soil could serve as an important carbon sink, especially in second-growth forests at mid- to high-latitudes (Dixon et al. 1994).

The rate of soil organic carbon sequestration depends on the complex interaction between climate, soils, tree species, and management practices (Lal 2005). Carbon in temperate forest soils is typically stored as soil organic matter, a mixture of recognizable plant and animal parts as well as humus, material that has decomposed to the degree that it no longer contains its original structural organization (Amundson 2001). About 60% of soil organic matter is carbon (Lal 2004a). Humus – what lends topsoil its rich, dark brown color – makes up the majority of soil organic matter. A small fraction of soil organic matter (0.2-4%) is made up of the microorganisms that break down soil organic matter, releasing it into the atmosphere in the form of carbon dioxide (Amundson 2001).

Temperature and moisture, along with the chemical and physical composition of the soil, are the major controllers of decomposition rates of soil organic matter (Lal 2004b). The activity of soil microorganisms increases with temperature, approximately doubling for each 10°C increase in temperature (Kirshbaum 2000). The relationship between precipitation and decomposition is not linear; rates of organic matter decomposition are highest at intermediate ranges of soil moisture (Amundson 2001). Excessively high water content ultimately leads to anaerobic conditions, which greatly reduce decomposition rates and increase soil carbon residence times (Amundson 2001). It is therefore important to conserve wetlands, which have slow decomposition rates and thus long residence times for stored carbon.

Managing soils for increased carbon stocks will be an important aspect of forest management for carbon sequestration, yet the science of soil management for carbon sequestration and storage is still being developed. While afforestation and similar land-use conversions generally increase the soil organic carbon pool, simply increasing production of forest biomass in an existing forest may not necessarily increase the soil organic carbon stock (Lal 2005). The soil carbon stock can be enhanced by ensuring adequate soil drainage and minimal soil disturbance, growing species with a high net primary productivity, and conserving soil and water resources (Lal 2005); however, it should be noted that accumulation of soil carbon in mature forests is a long process, occurring over decades to centuries rather than months. Soil erosion has the most impact on soil carbon storage of any soil degrading process (Lal 2004a); thus, preventing erosion through measures such as harvesting timber in the winter – when the soil is frozen – should be one of the top priorities of any management plan for carbon sequestration.

Clear-cutting and whole-tree harvesting techniques can lead to sharp declines in soil carbon stocks due to decreased litter input, shifts in abundance of woody and herbaceous vegetation, changes in depth distribution of plant roots, altered soil water and temperature regimes which accelerate decomposition, and a decrease in net primary productivity (Lal 2005; Johnson and Curtis 2001; Jackson et al. 2000). However, careful harvesting that minimizes disturbance to the soil and leaves behind a large amount of harvest residue would not only cause little or no immediate reductions in soil carbon stocks, but could possibly even lead to increases in forest floor carbon (Lal 2005; Johnson and Curtis 2001). However, these processes have not been well-studied in selectively harvested forests. Simulations of tree removal in the Green Mountains estimate that soil carbon stocks increase temporarily post-harvesting, followed by decreases in soil organic carbon that can take several decades to recover (Johnson et al. 2009). The models estimate that soil carbon stocks will decrease over several centuries of repeated harvesting, although the rate of decrease depends on the amount of biomass removed and the rotation period (Johnson et al. 2009).

There are some drawbacks to relying upon soil carbon stores for carbon sequestration; like the carbon stored in vegetation, soil carbon stocks are vulnerable to natural disturbances such as fire, wind, and changes to the ecosystem due to insects and diseases (Lal 2005). Disturbances that change the soil temperature and moisture regime, including fires, overharvesting, and climate change, can lead to massive, long-lasting releases of soil carbon into the atmosphere. As soil carbon sequestration has myriad additional benefits beyond the possible mitigation of anthropogenic climate change – soil carbon stocks are important for nutrient and water retention in the soil, filtration of pollutants, and the reduction of sediment loading in streams and rivers (Lal 2004a) – it will remain important to manage forests for general health in order to reduce their vulnerability to disturbances that could impact soil carbon stores.

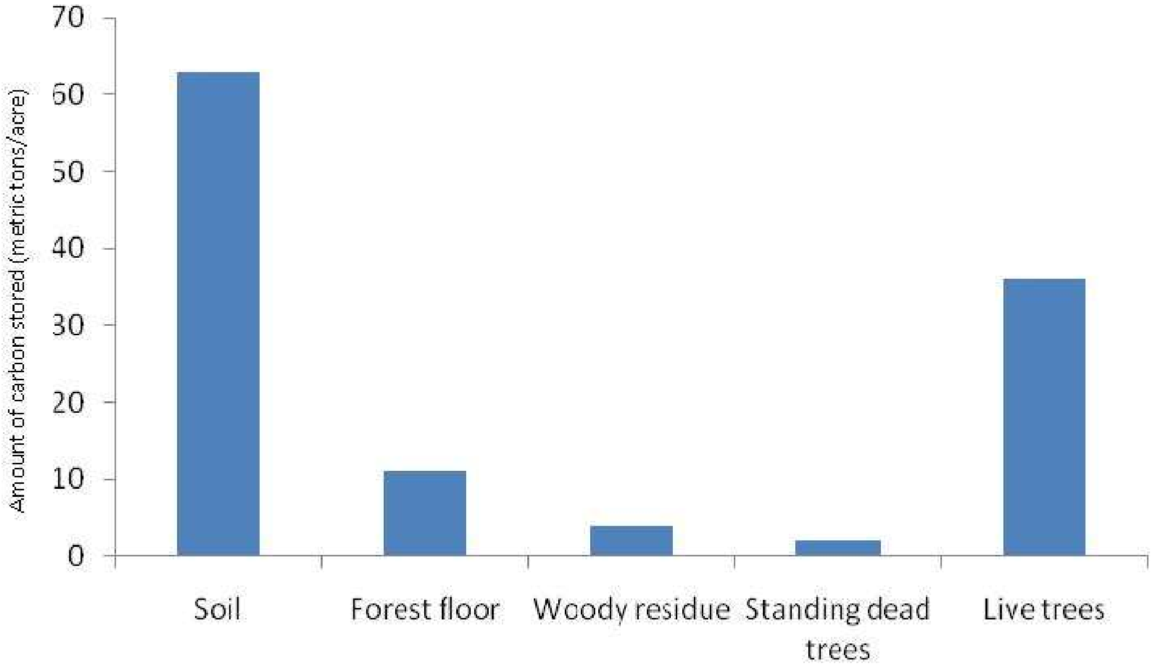


Figure 10. Carbon content of forest stores in Vermont (modified from NEFA 2002).

4.3 How does soil type affect carbon sequestration and storage?

The soil organic carbon stored in forest soils depends upon the type and age of the soil. The soil organic carbon concentration can range from 0% in very young soils to as much as 50% in some organic or wetland soils, with most soils containing between 0.3% and 11.5% in the top 20 cm of soil (Lal 2005).

Soil orders vary in their capacity to store carbon. The density of soil organic carbon found in the main soil orders of central Vermont ranges from 17 tons/ha to 1170 tons/ha (Lal 2004a). Rocky land, which lacks the carbon-rich topsoil of other soil orders, contains only around 17 tons/ha soil organic carbon. Alfisols, the predominant agricultural soils of the Champlain Valley, contain approximately 125 tons/ha soil organic carbon. Spodosols, the forest soils of the Green Mountains, contain around 191 tons/ha. Finally, histosols, which are wetland soils, contain a staggering 1170 tons/ha of soil organic carbon. It will be important to protect histosols, with their incredible carbon storage capacity, from degradation.

4.4 How does tree species composition affect carbon sequestration and storage by soil?

Trees differ in their rooting structure and depth, which influences the amount of carbon that is deposited in the soil from root litter, the plant's belowground soil carbon input (Kogel-Knabner 2001), and in the amount of their aboveground inputs. According to Heath et al. (2003), coniferous forest types such as spruce-fir and white-red-jack pine communities have greater soil carbon density (to a 1-meter depth) than deciduous forests.

Certain tree species also break down more quickly than others due to differing chemical compositions. Tree species have slightly different compositions of plant compounds such as cellulose and lignin, each of which varies in its rate of decomposition; for example, hemicelluloses are often the first compounds to be broken down, while lignin is often among the last to decompose (Yadav and Malanson 2007; Kogel-Knabner 2001). These differing chemical compositions are why soil organic matter breaks down more slowly in forest soils than in agricultural soils, as crop residues generally contain less lignin than forest litter (Yadav and Malanson 2007). It is possible that managing for tree species with slower decomposition rates will enhance the forest's carbon storage capacity. Unfortunately, there are major gaps in the knowledge on organic chemical composition of the species contributing to soil organic matter under pasture, arable land, and forests; the variability of different components, such as tannins and lignin, is only known for a few species (Kogel-Knabner 2001). Until these data are known, it will be difficult to assess the relative contribution of different tree species to soil carbon sequestration and storage.

4.5 How should a landowner manage for carbon sequestration?

If the goal of a landowner is to manage strictly for carbon sequestration, current knowledge suggests that passive management is the best management strategy. Although research on forests in the Southern Appalachian Mountains suggests that sequestration can be increased by diameter limit and selective cutting, these findings have yet to be replicated in the northern hardwood forest characteristic of Vermont (Davis et al. 2009). Although these harvesting regimes have yet to be evaluated in the northern hardwood forest, models of total soil carbon in Vermont forests find decreasing values under almost every harvesting scenario over a 360-year time scale. The only harvest regime that potentially led to a gain in soil carbon over time was 120-year rotations with 20% biomass removal. In one model of the forest carbon cycle, this regime yields a 0.7% increase in soil carbon in one model, while another model showed a 3.2% decrease in soil carbon stores (Johnson et al. 2009). Regardless of the model, however, these values are lower than those derived from no-harvest regimes, which had gains of 9.9% and 3.1%, respectively.

Neither model predicts gains in aboveground productivity as a result of harvesting. Increased rates of tree growth due to harvest will boost aboveground sequestration; this may partially counteract post-harvest losses in soil carbon in terms of total carbon accounting. In addition to this increase, the general assumption is that any carbon in timber removed from the forest will be permanently sequestered. For carbon removed from the forest as firewood or biomass, this is not the case—burning this wood quickly returns the carbon to the atmosphere. In principle, only long-lived wood products (e.g., furniture, construction materials) have the potential to make active management beneficial by sequestering forest carbon for long periods of time. Life-cycle analysis of wood products is not encouraging on this point, however: more than 60% of a tree's carbon can be lost during the manufacturing process for some species, and the lifespan of wood products varies dramatically (Harmon et al. 1996). Even when accounting for the carbon stored in wood products, unmanaged northern hardwoods sequestered at a minimum 28% more carbon than forests under active management (Nunery and Keeton, in press).

In addition to findings documenting the ineffectiveness of wood-product carbon storage, recent work on old-growth forests suggests that they may remain potent carbon sinks centuries after harvest (Luyssaert et al. 2008). Despite slower growth in older forests, these areas have high levels of carbon storage due to accumulated soil carbon and coarse woody debris. While it is true that harvesting large, slow-growing trees opens the canopy to allow for fast-growing younger trees, the large amounts of carbon that are lost from the various carbon pools in a forest (e.g., soil, trees) as a result of the harvesting appears to be much greater than the carbon sequestered by these younger trees. After older trees die, they replaced by younger individuals that grow to the canopy. In the case of an unmanaged forest, these older trees retain their carbon: decomposition of large dead trees can take decades, further increasing the carbon store of the older forest. While these forests could potentially become carbon sources due to rates of decay, current knowledge suggests that sequestration may continue for up to 800 years (Luyssaert et al. 2008).

Regardless of age, models of post-harvest soil carbon show that management decreases the sequestration of northern hardwood forests. Given that wood products have been shown to be only weak carbon sinks and that older forests continue to sequester carbon, we find that even a 20% removal of biomass every 120 years decreases the carbon storage of the ecosystem as compared to an unmanaged forest (Johnson et al. 2009).

Although untested, some active forest management may potentially increase sequestration by mimicking natural disturbance: felling and girdling trees could both increase slow-decomposing dead wood while promoting new growth. However, these management strategies have not yet been empirically evaluated, and given current knowledge, passive management (i.e., no harvest) appears to maximize carbon sequestration in the northern hardwood forest.

4.6 How can a landowner manage for carbon sequestration and timber harvest?

Sustainable forestry is based on maintaining future soil productivity and timing tree harvest as growth rate begins to decline. Volume growth per year is sigmoidal, peaking during the middle of an individual's life span and declining thereafter (Saastamoinen and Matero 2008). Older trees are removed in favor of younger, fast-growth individuals, maximizing aboveground productivity over time.

Management for carbon sequestration is often assumed to be identical to sustainable harvesting practices. While the addition of carbon to tree biomass is greatest at the time of highest tree growth, this does not directly correlate to peak carbon sequestration in the forest (Meng et al. 2003). Carbon in soil and dead wood make up the majority of storage in the ecosystem, and both of these pools rely heavily on older trees to produce coarse woody debris and leaf litter. Instead of simply examining the increase of live carbon biomass, harvesting models must take into account the rate of carbon accumulation (and conversely, rate of loss) in soil and woody debris pools.

The tradeoff between increased aboveground sequestration due to harvesting and loss of soil carbon after harvest is central to understanding forest carbon storage. Soil carbon stocks generally decline following harvest due to soil disturbance, root decay, and decreased leaf litter input (Jandl et al. 2007). To predict optimal rotation length, models must incorporate the decline and replenishment of soil organic carbon, as well as the increases to aboveground productivity following harvest. Management for carbon sequestration must at least replenish the total carbon within the system between rotations.

Studies from coniferous plantations find that while shortened harvest intervals increase the rate of tree carbon sequestration due to growth, the amount of carbon stored in the soil decreases (Liski et al. 2001). The authors also recommend a greater rotation length (a change from 90 years to 120 years) to increase total carbon storage, although this practice reduces landowner revenue. Trees in these plantations took 90 years to reach peak aboveground sequestration rates, but the build up of decomposing organic matter in the soil takes longer to reach an optimal level of carbon (Liski et al. 2001).

With respect to hardwood species, harvesting in a Central Appalachian forest led to an increase in carbon storage as compared to an un-harvested forest. Carbon sequestration decreased over the short term following harvests, but total carbon sequestered over a 55-year period was 37% greater in areas subject to diameter-limit and selective cutting than carbon in an unmanaged plot (Davis et al. 2009). Empirical work of this kind has not been carried out in the northern hardwood forest. The existing research has found both gains and losses for total carbon in managed forests. Until a study is conducted in Vermont that fully examines this question, we cannot make definitive management recommendations based on the results of one study, particularly one taking place in the warmer, nitrogen-rich soil of West Virginia.

Harvest management must now focus on methods of timber removal that increase aboveground productivity while maintaining soil carbon storage. Knowledge of appropriate timescales for these rotations in the northern hardwood forest is limited, making management prescriptions difficult. While the peak of harvestable timber generally occurs between 60 and 90 years, recent work finds that hardwood forests continue to act as efficient sinks despite attaining old growth age (Luyssaert et al. 2008).

One modeling effort has examined the effects of harvest frequency and intensity on carbon in Vermont forests (Johnson et al. 2009). The study deals only with soil carbon, but has tangible implications given its importance in carbon storage. Beginning with a soil carbon baseline scenario of a clearcut, and followed by 80 years of regrowth (a typical history for Vermont forests), almost all harvesting scenarios lead to a decrease in total soil carbon over a 360-year period (Johnson et al. 2009) Of the thirteen management regimes tested, only two regimes – no-harvest and 120-year rotation, 20% biomass removal – showed increased soil carbon. Decline from scenarios of current practices (90-year rotation, 40% biomass removal) is generally less than 10%, however, suggesting that increases in aboveground biomass or mitigation options may provide a way to make harvesting carbon neutral.

Aboveground forest carbon was not included in the Johnson et al. (2009) model, underscoring the fact that we still do not know the total effects of harvesting on the carbon within the northern hardwood forest. Given the findings of Davis et al. (2009), aboveground productivity of the forest following harvest may offset loss of soil carbon under some harvesting scenarios. A definitive model of harvesting and carbon in the northern hardwood forest has yet to be developed.

Until empirical research and modeling can fully address these questions, we recommend lengthening rotation time beyond durations considered appropriate for sustainable forestry in order to increase carbon stored. Further work must ultimately identify a combination of harvest intensity and frequency where post-harvest declines in coarse woody debris and soil carbon are offset by an increase in the productivity of aboveground biomass.

4.7 What role does fertilization play in managing forests for carbon sequestration and storage?

While fertilizer has long been used to enhance aboveground productivity in plantation forests in many parts of the country, the effects of forest amelioration on carbon storage are just beginning to be explored. Initial results appear inconclusive because nitrogen added has led to both gains and losses in total carbon storage (Adams et al. 2005; Jandl et al. 2002). This variability is likely due to differences in soil type, latitude, and pre-fertilization nitrogen levels.

Although forests in the Northeastern U.S. exhibit elevated nitrogen levels due to anthropogenic deposition, carbon sequestration in the northern hardwood forests may be nitrogen limited (Lal 2005; Johnson et al. 2009). Fertilizer is rarely, if ever, applied to the northern hardwood forest given its slow growth rate relative to coniferous plantations, and not much is known about its effects (Marc Lapin, personal communication). Given that some studies predict that nitrogen limitations will increasingly inhibit sequestration as CO_2 levels increase, we recommend that future experiments address the costs and benefits of post-harvest nitrogen application to increase carbon sequestration (Wamelink et al. 2009).

One model of total soil carbon predicts that sequestration may be limited by a lack of available nitrogen after harvest, but empirical work is needed to confirm this hypothesis (Johnson et al. 2009). At present, we cannot recommend fertilizing northern hardwood forests given the paucity of data available on the subject. As the issue of carbon sequestration in the northern hardwood forest continues to gain momentum, we expect future work to explicitly address the question of fertilization.

4.8 How do previously proposed standards for biomass procurement affect carbon sequestration and storage?

The current standards for harvesting for Middlebury College should come from those recommended by the ES 401 Fall 2009 report (ES 401 2009). However, some of these standards have a negative impact on the ability of the forest to sequester carbon and should be modified to maximize the carbon sequestration potential of the forests. The following standards of ES 401's recommendations should be considered further:

- "*Average annual removal of woody biomass from the site should not exceed 70% of the average annual growth*."

  This standard allows for too much biomass removal, which could negatively impact carbon sequestration in the forest. It is recommended for maximum carbon sequestration that much less of the biomass is harvested in order to leave more biomass in the forest that cannot only store carbon that is already in the forest but also can continue to sequester more carbon from the atmosphere.

- "*Retain at least 2 down trees or logs per acre exceeding 14 inches in diameter on average*."

  This recommendation is not as rigorous as the recommendation of Vermont Family Forest, which suggests in its Town Forest Health Check that "there are a minimum of four downed trees of 16+ foot long logs per acres on average, with one exceeding 21" DBH and four exceeding 15" DBH." While there is no information on what these statistics are based on, it cannot be assumed that these same recommendations are viable for maximum carbon sequestration. The recommendation for downed woody debris for maximum carbon sequestration rates is complicated by the fact that in unharvested forests, which sequester more carbon than harvested forests (Yanai et al. 2003), the woody litter pools are never constant, so one cannot determine at which point the most beneficial amount of woody debris occurs. However, from these points, one can suggest that retaining the most down trees possible is best for carbon sequestration since downed trees are an important carbon sink.

- "*Cutting cycles should be between 10 and 15 years minimum*."

  For maximum carbon sequestration, forests should not be cut (Johnson et al. 2009). For greater detail, please refer to Section 4.5

- *"Prioritize the safety of any potential individuals who might use the site for recreation."*

  Sites maintained for maximum carbon sequestration should not be used for recreation. Due to the sensitivity of soils to erosion, these forests need to be preserved from exterior forces in order to maintain the maximum carbon sequestration potential in the soils and in the general forest. Considering there are other areas and parks available for recreation, it is possible to leave these designated forests along in order to maintain their carbon sequestration potential.

- "*Maintain the natural aesthetic to the maximum possible extent.*"

  Under this general recommendation, it is suggested to: *"Lob treetops 2 feet or less in high use areas.* " This recommendation would eliminate the young growth in high use areas that is instrumental in increasing carbon sequestration rates in a forest, since young trees have greater carbon sequestration rates when compared to stands of old trees. By lobbing the treetops, many of the leaves would be lost, and photosynthesis occurs in the leaves, so this recommendation would dramatically decrease the photosynthetic abilities and carbon sequestration. Therefore, any regard to aesthetics of the forest should be ignored in order to preserve the forest's ability to sequester carbon.

If these changes are made to the procurement standards, then Middlebury College's biomass will be obtained from forests where there is maximal carbon sequestration, thus advancing the carbon neutrality goal of the College.

4.9 How will climate change affect carbon sequestration and storage?

Climate change is expected to change the temperature and moisture regimes of the Northeastern U.S., affecting the capacity of northern hardwoods forests to sequester and store carbon. There are myriad predictions for how forest carbon storage will change over the coming decades to centuries, most of which are highly uncertain, even contradictory. Climate change may stimulate forest growth by enhancing availability of mineral N and through the CO_2 fertilization effect, thus increasing both carbon sequestration and storage (Lal 2005). Yet it appears likely that warming will also have the effect of reducing soil organic carbon by stimulating microbial activity more than forest growth (Kirschbaum 2000). However, as increasing CO_2 is likely to simultaneously have the effect of increasing soil organic carbon through increases in net primary productivity, the net effect of changes in soil organic carbon on atmospheric CO_2 over the next decades to centuries is likely to be small (Kirschbaum 2000). The possible changes to soil moisture will be important for determining whether northern forests continue to act as carbon sinks; while moderate increases in soil moisture are likely to increase carbon storage in mid-latitude forests, reductions in soil moisture and increased plant respiration associated with warming are likely to reduce carbon storage (Melillo et al. 2002).

Other likely effects of climate change include warmer winters and wetter, warmer summers, with a variety of possible consequences. The species composition of northern hardwoods forests is expected to change over the coming decades to centuries; for example, oak-hickory forests are predicted to grow in dominance as maple and beech forests decline, and white pine is expected to expand its range as balsam fir migrates northward (Iverson and Prasad 1998). Reduced soil freezing in the winter would likely lead to reduced access for winter logging and increased soil disturbance and erosion during winter harvesting (Spittlehouse and Stewart 2003). Wet, warm summers would likely lead to increased invasion by insects, diseases, and exotic species

(Spittlehouse and Stewart 2003). Forests should be managed to reduce vulnerability to and enhance recovery from these invasions.

It would be irresponsible to make management recommendations based on highly uncertain predictions; however, forest managers should be aware of the possible changes to the forest ecosystem and continue to adapt their management strategies to the most recent and relevant research.

5. Tools for Carbon Sequestration

5.1 What are the financial incentives for sequestering carbon?

Forests and forest products are beginning to gain recognition in market-based policy instruments for climate change mitigation (Malmsheimer et al. 2008). Some forestry projects qualify as carbon dioxide emission reduction credits for trading to offset emissions from industrial and other polluters. Depending on the program, several project types may be eligible: afforestation, reforestation, forest management to protect or enhance carbon stocks, harvested wood products that store carbon, and forest conservation or protection (Malmsheimer et al. 2008).

Currently, the Regional Greenhouse Gas Initiative, a recently implemented mandatory cap-and-trade program for large emitters in ten Northeast states, including Vermont, limits eligibility to afforestation projects; at least in the short term, landowners cannot receive payment through these programs for forest management for carbon sequestration. The other mandatory cap-and-trade emissions program in the U.S., the California Climate Action Registry, permits credits for afforestation, managed forests, and forest conservation, and it is possible that new cap-and-trade carbon markets will emerge over the next decade (Malmsheimer et al. 2008).

5.2 What are the costs to the landowner of managing for carbon sequestration?

Our current understanding finds that managing land strictly for carbon sequestration will be of no direct cost to the landowner because passive management of land doesn’t cost anything to implement. However, passive management has opportunity costs, in that the potential economic benefits of firewood and timber harvesting will be foregone if one manages strictly for carbon storage through a no-harvest regime.

The landowners may also be forced to remove their land from prior conservation easements or Current Use agreements. While conservation easements do not generally mandate regular harvesting intervals, removal is virtually guaranteed in the case of Vermont’s Current Use program. Forestland must be actively managed to qualify for this program in Vermont, and this stipulation does not include passive management for carbon sequestration. It is also unlikely carbon sequestration will be added given present attempts to scale back program funding.

If harvesting is to take place, harvesting with carbon sequestration in mind (i.e., longer rotations, no whole tree harvesting, minimizing erosion, and leaving slash on site) can ensure the economic benefits mentioned above while still managing land to promote future sequestration and maintain existing soil carbon.

5.3 How would new management standards affect the cost of biomass procurement?

Our knowledge of the costs associated with procuring biomass is largely informed by the work of the ES 401 Fall 2009 report (ES 401 2009). Given the significant overlap between their procurement recommendations and our addendums that focus on carbon sequestration, we do not foresee a significant increase in cost to implement our standards.

The one suggestion that may increase cost above the procurement standards of ES 401 is to further increase recommended rotation length. This increase will likely reduce owner income from the land, raising the cost of harvest. Based on our limited knowledge of sequestration rates, we can only recommend an increase in rotation length over business as usual (i.e. rotations of 90 years instead of the usual 60 years for a parcel) as a means to increase carbon storage, so this increase in cost will be on a case-by-case basis.

6. Researching Carbon

6.1 What is missing from the scientific literature that needs to be researched?

While researching biomass procurement standards and their ability to promote carbon neutrality by increasing carbon sequestration, there were several areas of study for which little to no information could be found in the literature. As current research stands, the carbon sequestration potential for a certain region is virtually impossible to know without specific studies and measurements of that area.

- ***Development of annual carbon storage equations based on stand age and site index for the northern hardwood forest and other forest types*****.—**The development of easily parameterized ecosystem-specific models for predicting annual forest carbon storage is essential to carbon accounting. Gough et al. (2008) developed an annual carbon storage equation for aspen-dominated forests, but this equation is not specifically applicable to other forest community types. The development of more ecosystem-specific equations is therefore necessary for the universal calculation of annual forest carbon storage.

- ***Specific measurements of carbon sequestration rates for northern hardwood forests.—*** Carbon sequestration rates need to be measured for specific areas relating to Middlebury College and northern hardwood forests in general. Several of the studies (Malmsheimer et al. 2008; Stavins and Richards 2005) that include information on sequestration rates for certain regions are based on a vague report titled "Costs of Creating Carbon Sinks in the U.S. (Richards et al. 1993), which does not clarify exactly where the data were measured. This information needs to be clearer and more easily calculated for specific regions. A database that includes the carbon sequestration rates and peaks for each tree species would be extremely useful for deciding management standards and afforestation decisions (Lal 2003). However, these calculations would then need to be manipulated based on the specific composition of each forest, so generalized calculations for certain types of forests would be equally useful. However specific these calculations could be made, they would ultimately still be rough estimates due to the many factors (soil type, climate, nutrient balance, soil quality, disturbances) that affect carbon sequestration potential and measured sequestration rates for specific trees and forest types.

- ***Global climate change and effects on northern hardwood forests and soil.*****—**Climate change may further complicate calculation of carbon sequestration because the associated environmental changes could have dramatic effects on sequestration rates as well as storage capacities of soils. While it can be approximated what types of trees will move into certain areas over an estimated time range, further study is needed on the impacts on soil carbon storage that climate change will bring. As this report has stated, soil is a large component in sequestering carbon, and without healthy soil, sustainable forests cannot be maintained, and biomass accumulation and additional carbon sequestration are affected. In general, a greater analysis of the changes found in the entire ecosystem, with a focus on changing soil qualities, needs to determine the total effects of the changing environment on its ability to sequester carbon.

- ***Verify uncertainties of calculations*.—**Most importantly, the uncertainties of these calculations need to be clearer. Many of these calculations are made on models, and the error terms associated with such models necessarily becomes a large component in understanding the possibilities of carbon sequestration and its ability to aid in carbon neutrality issues. The error greatly affects the precision of calculations, and yet studies infrequently emphasize the generalizations made. Further work must either work to eliminate sources of error, which would come at the cost of furthering carbon sequestration research, or to explain the generalizations used and to explain why these assumptions are viable.

- ***Soils.*—**The effect of different soil types on carbon sequestration potential needs to be clearer. There is growing evidence that the clay mineralogy of different soils affects their ability to sequester carbon, but the data are not yet clear enough to make specific recommendations for the protection of soils containing different clay minerals. There is a lack of data to support this claim and any others about the most beneficial soil type for carbon sequestration as it relates to carbon neutrality.

- ***Fertilizer and its effects on sequestration rates*.—**Fertilizer has the potential to significantly increase biomass accumulation rates and thus carbon sequestration rates. However, no studies have thoroughly examined the effect of fertilizer on total forest carbon sequestration in the northern hardwood forests.

- ***Successional changes in sequestration rates*.—**Sequestration rates are dependent upon many different forest variables, including climate, soil composition, and species composition. With successional changes, these factors could change drastically, thus altering significantly the carbon sequestration rates of the area. The effects of successional changes on sequestration rates need to be measured and clarified.

6.2 What is outside of the scope of this project that the College should research?

This project focuses mainly on synthesizing the literature on carbon sequestration into recommendations of how land can be managed to optimize carbon sequestration and what standards Middlebury College should use for procuring biomass. There are, however, many aspects of the actual application of these recommendations that are beyond the scope of this project. These aspects primarily involve economics and specific data collected from college lands or lands from which biomass is obtained.

This report does not delve into the economics of biomass procurement, which would certainly need to be investigated further before the recommended standards were actually put into place. Additionally, the economics of afforestation or restoration projects that may increase the amount of carbon sequestered on Middlebury's lands have not been addressed. Such projects could be important steps toward the College's goal of carbon neutrality by 2016, but cannot be undertaken until the economic tradeoffs of converting agricultural land to forest have been fully assessed. A more detailed understanding of exactly how much additional carbon would be sequestered through such projects would also be needed before determining whether or not they were worth undertaking.

Several avenues for estimating carbon sequestration have been discussed in this report (Section 3.1). It is outside the scope of this project to determine which, if any, of these approaches is the best for Middlebury College to undertake. The actual decision to follow one of the approaches would require further investigation into both the technical and labor expenditures that would be needed.

7. Summarizing Carbon

7.1 How should land be managed for carbon sequestration and storage if timber harvesting is a management goal?

- ***Promote mixed-species, mixed-age stands***.—These stands tend to have higher carbon uptake and storage because of their higher leaf area (Kelty 2006). Furthermore, mixed stands include species that are both shade tolerant and intolerant so that there are trees that grow successfully at all levels; this leads to maximum increase in biomass, which enables more carbon sequestration. Finally, mixed stands enable forests to withstand outbreaks of disease and insect infestation so that even if one type of tree succumbs to disease, the other species of trees are able to survive and to continue to sequester carbon. Therefore, landowners should follow these recommendations in order to sequester the maximum amount of carbon in forests.

- ***Protect soils***.—Soils in temperate forests hold about 60% of the total carbon in these forests (Dixon et al. 1994). In order to maximize the soil carbon stock, adequate soil drainage must be maintained, and soil disturbances must be minimized. Furthermore, soil carbon stocks can be increased by growing species with high net primary productivity so that more nutrients are released back into the soil, which can be stored in the soil for long periods of time. These guidelines are especially important during harvesting, when forest soils are more prone to erosion and water contamination. Great care should be taken to avoid exposing mineral soil, which lies deep in the soil profile and is typically a stable carbon store. Only harvesting practices that protect mineral soils should be used.

- ***Protect wetlands in addition to forests***.—Histosols are a soil type found in most wetland soils and contain approximately 1170 tons/ha of soil organic carbon. Histosols can contain much more carbon than alfisols and spodosols, the principle soil types of the Champlain Valley and the Green Mountains. Therefore, wetlands and hydric soils of any kind must be protected in order to maintain the soil quality and the capacity to sequester carbon.

- ***Passive management***.—Management practices for maximum carbon sequestration should emphasize passive management practices. Unmanaged northern hardwoods still sequester more carbon than forests under any active management, and unmanaged forests may continue to sequester carbon for up to 800 years (Luyssaert et al. 2008). Even if harvested wood becomes furniture, construction materials, or other long-lived wood products, they still might not store atmospheric carbon as much as previously thought (Harmon et al. 1996). There has been a 26% increase in carbon from an actively managed forest, even if wood from the forest is put into furniture (Nunery and Keeton, in press). Some untested active management practices that mimic natural disturbances could promote new growth in the forest, but until these practices are tested further, we recommend passive management to maximize carbon sequestration in forests.

- ***Maintain high levels of down trees, dead standing timber, and coarse woody debris*.—** While specific numbers of down trees to leave in the forest following harvesting cannot be determined due to the imprecision of the science, harvesting and management practices should maximize the amount of down trees and coarse woody debris left in the forest so that these trees and debris may continue to store carbon.

- ***Leave slash and logging residue behind.*—**Similar to down trees, dead standing timber, and coarse woody debris, slash and logging residue contain carbon. They break down faster into humus, and therefore contribute more carbon to the soil carbon store.

- ***Maintain continuous cover to keep soil temperature low and to keep some litter falling each year.*—**Soil temperature is linearly related to microbial activity; thus, maintaining a lower soil temperature will help to maintain lower rates of soil organic carbon decomposition in the forest, thereby decreasing the amount of carbon released back into the atmosphere. Also, litter needs to continue to fall each year to maintain the amount of carbon that is returning to the soil carbon store from the biotic stores. By maintaining this continuous carbon cycling, more carbon can continue to be stored in the soils of northern hardwood forests.

7.2 What should Middlebury College do with respect to biomass procurement?

Below we repeat the recommendation made in the ES 401 Fall 2009 report (ES 401 2009), amended with recommendations (noted in italics) to improve the standards with respect to carbon sequestration and storage.

Sustainable Forestry

1. **Forest management goals will be developed with a professional forester while using recognized silvicultural guides.**
    a. **Due to variability in forest stands due to physical site conditions and past harvests, cutting and silvicultural techniques will vary.**
    b. **In developing silvicultural techniques for meeting management goals, a combination of the forester's professional judgment and the recognized silvicultural guides, including but not limited to:**
        i. A Silvicultural Guide for Northern Hardwood Types in the Northeast by Leak, Solomon and DeBald;
        ii. A Silvicultural Guide to White Pine in the Northeast by Lancaster and Leak;
        iii. A Silvicultural Guide for Spruce-Fir in the Northeast by Frank and Bjorkman;
        iv. A Silvicultural Guide for Developing a Sugarbush by Lancaster, Walters, Laing and Foulds;

v. Uneven-Aged Management of Northern Hardwoods in New England by Leak and Filip;

vi. A Landowner's Guide to Wildlife Habitat Management for Vermont Woodlands by Vermont Fish and game Department;

vii. Manager's Handbook for Red Pine in North Central States by North Central Forest Experiment Station, U.S.D.A. Forest Service;

viii. A Guide to Hardwood Timber Stand Improvement by U.S.D.A. Forest Service, Northeastern Area State and Private Forestry; and

ix. Establishing Even-Age Northern Hardwood Regeneration by the Shelterwood Method- A Preliminary Guide by North Central Forest Experiment Station, U.S.D.A. Forest Service.

c. **Sustainable harvesting must consider biodiversity as forest management and utilization have impacts on population of all forest organisms. Different silvicultural techniques have varied effects on biodiversity.**

d. ***Promote mixed-species, mixed-aged stands.***

Use uneven-aged management by area regulations whenever possible. Uneven-aged, mixed-species stands tend to have higher carbon uptake and storage because of their higher leaf area and are generally less vulnerable to outbreaks of disease and infestation by insects.

2. **Average annual removal of woody biomass from the site should not exceed 70% of the average annual growth.**

a. **Avoid clear-cutting. Canopy openings should be less than 0.25 acres and no larger than 1.25 acres.**

The natural pattern for open patches in northern hardwood and spruce-fir forests of northern New England is one of small, disturbed patches within an area of older forest. Harvesting in large, open patches introduces a patch structure significantly different from the natural pattern in these forests. Small-patch silvicultural techniques best mimic the natural pattern.

b. ***Whenever possible, maintain continuous canopy cover to maintain low soil temperatures and uninterrupted litterfall.***

Soil temperature is linearly related to microbial activity; thus, maintaining a lower soil temperature will help to maintain lower rates of soil organic carbon decomposition in the forest, thereby decreasing the amount of carbon released back into the atmosphere. Maintaining a continuous litterfall will help ensure that an *adequate amount of carbon returns annually to the soil carbon store from the biotic stores.*

3. **Biological legacies of the forest community should be protected to retain forest productivity and health.**

   a. **No whole tree harvesting**

   Whole tree chipping damages forest ecosystems by depriving soils of important nutrients deriving from residual branches and tops. These features also serve to provide habitat to a variety of wildlife.

   b. **Retain at least *4 down trees or logs per acre* exceeding *15 inches in diameter on average.***

   Wood-chip harvests often consist of clear-cutting or whole tree harvesting, including the removal of branches and leaves. These types of harvesting often result in decreased levels of nutrients, including losses of calcium, nitrogen, potassium, magnesium and sulfur. Utilizing forests alters nutrient cycles as nutrients are stored in roots, stems, branches and foliage of plants and in the forest floor litter. Different harvest intensities and silvicultural techniques should reflect the ecosystem's susceptibility to nutrient depletions. The ability of a forest to recover from a harvesting event is related to the amount of wood left on-site.

   Coarse woody debris left at the site after logging is important for forest carbon storage and numerous other ecosystem processes. "Dead wood is an extremely important aspect of the forest structure…coarse woody debris serves as seed germination sites, reservoirs of moisture, and habitat for numerous species of fungi, invertebrates, and vertebrates; it also plays important roles in nutrient conservation and cycling."

   c. ***Tree tops, branches, leaves, needles, and all material less than 4 inches in diameter are left in or near where they were felled***

   Branches and foliage contain the largest amount of nutrients – including carbon – in trees, and in order to adequately maintain nutrient pools and cycles it is necessary to leave foliage and branches dispersed in the forest.

4. ***Thinning* cycles should be between 10 and 15 years minimum*, and only occur if it can be done in a way to not disturb soils in such a way as to release carbon that is stored there*.**

   a. ***Minimize intermediate treatments to maximize carbon sequestration and storage.***

   Intermediate treatments should generally raise the average diameter of the residual dominant and co-dominant trees of the forest while improving timber quality.

However, each harvest, with its associated soil degradation and other forest damage, can lead to decreases in total carbon sequestration and storage, and the number of intermediate harvests should be kept at a minimum.

5. **Harvesting will promote the protection of residual trees.**

    a. **Residual stand damage should be confined to 10% or fewer of the dominant or co-dominant trees.**

    b. **Great care should be taken to avoid basal wounds on residual trees as basal wounds are ideal entry sites for decaying fungi and bacteria.34**

6. ***Harvest with the longest rotation period possible.***

    A forest is able to sequester more carbon if it is able to have longer rotation periods between harvesting. For optimal carbon sequestration and biomass production, we recommend 90-120 years. Due to this length in duration, several plots need to be in rotation.

Wildlife Habitat Protection

1. **Take steps to preserve Indiana bat habitat in areas conducive to their habitation.**

    Every effort should be made to protect Indiana bat habitat. This is an effort to preserve a species that is being threatened by white-nose syndrome, habitat destruction, and cave disturbances. Additionally, as one of two Vermont species listed as endangered, Indiana Bat habitat conservation is mandated by law. While the bats are rare, enough is known to log responsibly. This is an important contribution to a national effort and prevents the obvious issues raised by illegality. The greatest threat posed by our actions is the destruction of summer roosting and foraging habitat. Female bats bear their young in specific types of trees that are easily avoided. Practices should include:

    - Preserve snags whenever possible. Especially those naturally exposed to consistent sun.
    - Specific care should be taken in the southern Champlain Valley, the confirmed area of habitation.
    - Retain dead trees with a diameter of more than 12 inches located within 200 feet of streams, lakes, ponds, or wetlands.
    - Retain Shagbark Hickory and Black Locust.
    - Avoid entire areas with known roost trees.
    - Avoid road construction within 100 feet of known hibernacula.

- Log with a forester with knowledge of Indiana Bat Management Practices.

2. **Preserve 100-foot buffers of original vegetation between wetland, stream, pond or lake and active cutting areas. On steep slopes extend this buffer strip to 150 feet.**

   Riparian buffers offer diverse ecological services and are essential elements of responsibly managed land. They serve to filter suspended sediments from runoff - protecting against water eutrophication - provide habitat for large numbers of animals, stabilize banks, and regulate water temperature. Different conditions assure that buffer width varies at different locations. A broad average suggests that bank stability is preserved with 50 feet of buffer between water and the site; 100 feet assures better water quality due to sediment filtering; and 150 feet preserves habitat protection. 100 feet seems the most reasonable mark to impose. This width is adequate to remove suspended sediments and nitrogen from the runoff. Beyond this width, numerous small streams on a property could severely limit the productivity of a site. However, an additional site variable is bank steepness, with steep banks necessitating 150-foot buffers.

Water Quality

1. **Erosion and sediment control practices are required as outlined in *Acceptable Management Practices for Maintaining Water Quality on Logging Jobs in Vermont.***

   Soils in temperate forests hold about 60% of the total carbon in these forests. In order to maximize the soil carbon stock, adequate soil drainage must be maintained, and soil disturbances must be minimized. Soil conservation and management is also vital to conserve nutrient cycles. Logging causes nutrient loss through direct removal of nutrients stored in the harvested biomass, increased erosion, and elevated levels of nutrients leached by stream waters for several years following harvesting. Vermont's Acceptable Management Practices on Water Quality are well-developed and adequate for maintaining water quality, with several exceptions:

   - *avoid all spring and summer harvesting (and in the fall and winter, only harvest when the soil is adequately dry or frozen);*

   - *properly buffer and protect streams and special habitats such as cliffs, caves, talus slopes, beaver meadows, vernal pools, spring seeps, and remnant patches of old growth forest;*

   - *protect and preserve all areas containing histosols, a type of wetland soil that can contain approximately 1170 tons/ha of soil organic carbon, nearly 10 times the storage capacity of other soil orders;*

   - *avoid rutting that extends beyond the A soil horizon; and*

   - *re-seed exposed soil with native species to protect against erosion.*

Aesthetic and Recreation Considerations

1. **Prioritize the safety of any potential individuals who might use the site for recreation.**
    a. Before and during harvesting practices erect and maintain signs notifying recreational users of the harvesting operation and safety concerns.

    b. Consider notifying adjacent landowners as well as the town office of your operation to make the public aware of any potential hazards that may exist.

2. **Maintain the natural aesthetic to the maximum possible extent.**
    a. Maintain a buffer of at least 150 feet between landing areas and any class III or higher roads.

    b. Actively minimize the crossing of hiking trails when creating skid trails. Only cross trails at right angles.

    c. Maintain a buffer of at least 100 feet to hiking and recreation trails, unless absolutely necessary.

    d. Lop treetops 2 feet or less in high use areas. In areas with high deer population, leave slash high enough to protect new seedlings.

7.3 Which college lands should be especially protected for carbon sequestration?

It is extremely important that the college does not disturb any of the regions that contain histosol soils (Figure 11).

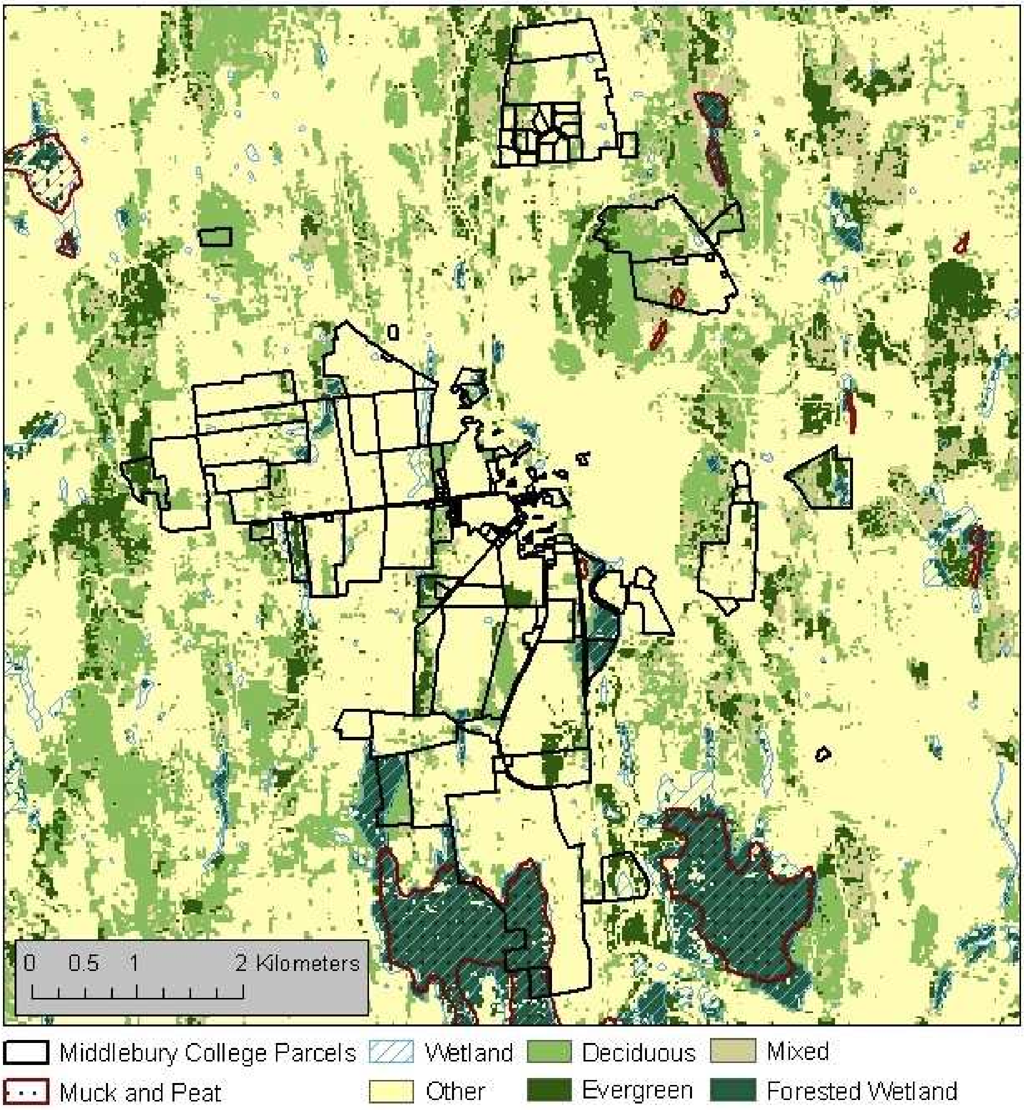


Figure 11. The distribution of histosol soils on land owned by Middlebury College. The histosol soils of Vermont are found primarily in muck, peat, and wetland habitat types. Other forested habitat types are shown for reference.

7.4 What other projects could the college undertake to sequester carbon?

Afforestation is the planting of forests in lands that have had other land uses, such as agriculture. This change in land use is beneficial because afforestation helps to enrich soils with more soil organic carbon and leads to increased carbon sequestration (Lal 2005). However, afforestation in northern hardwood forests has not been greatly studied, so its total effects are not known (Silver et al. 2000; Ross et al. 2002). Much of the literature supports the idea of afforestation in terms of carbon sequestration and increasing the soil organic carbon; the issue is over policy, especially here in Vermont. Family farmers need agriculture to stay in Vermont and possibly could not survive if there were governmental incentives for agricultural land to change to forests.

Middlebury College should look into economic incentives in order to support local farmers, possibly through agroforestry, so that farmers may continue to farm but also have tracts of forests.

Middlebury College owns over 1500 acres of agricultural land that could, in theory, be used for afforestation projects. In reality though, the vast majority of that land is currently being leased to farmers and used as crop fields or as pasture for dairy cows and is therefore unlikely to be available for afforestation in the foreseeable future. However, there are several areas on college land that are too wet to be used to grow crops and are not being used as pasture. Such areas, several of which are on the Palmer and Johnston lots, could potentially be afforested without encroaching on the livelihood of any farmers or threatening food supply. Further investigation would be needed before actually launching afforestation project on any lands, but it is an option that the college may want to consider in an effort to reach its goal of carbon neutrality by 2016.

7.5 What should Vermont Family Forest members do to manage forestlands for carbon sequestration?

VFF's Forest Management Checklist (Brynn 2008) consists of useful standards and management practices that landowners can follow to maintain healthy forest ecosystems. While the checklist is thorough, there are a number of standards that can be modified in order to maximize the carbon sequestration potential of VFF members' forestland. What follows are our recommendations (in italics) to the existing VFF checklist (in bold):

1. **Accessing the Forest: Skid Trails, Truck Roads, and Log Landings:**

   Avoid spring harvests and/or rutting that extends beyond the A soil horizon.

   Harvesting should never be done in the spring. To maximize the soil's ability to store carbon, it should instead be done in the winter. Harvesting when the soil is not completely frozen can disturb the soil and release large amounts of stored carbon.

   Properly buffer and protect special habitats such as cliffs, caves, talus slopes, beaver meadows, vernal pools, spring seeps, and remnant patches of old growth forest.

   In addition, take special care to protect wetlands, particularly those with histosol soils. Histosol soils are comprised of muck and peat and contain a thick organic layer capable of storing ten times as much carbon as other soils in the region.

2. **Accessing the Forest: Stream Crossings**

   Particular care should be taken to prevent stream bank erosion in order to avoid the release of stored carbon.

3. **Vegetation Management**

Promote an uneven canopy in the forest by creating small canopy gaps through natural processes or by cutting.

A forest is going to sequester and store the most carbon when it is left untouched. Therefore, we do not recommended creating canopy gaps other than those that are necessary when harvesting.

Any forest management in natural communities that are ranked as “very rare” (S1) and “rare” (S2) or in natural commuinities ranked at "uncommon" (S3), "common" (S4), and “very common” (S5) but with little or no evidence of past human disturbance should be reviewed and approved by the VT F&W Natural Heritage Biologists.

Wetlands with histosol soils need to be protected and preserved in order to maintain their ability to store large amounts of carbon.

In general, leave all materials that are less than three inches in diameter on the site.

In addition, leave as much biomass on site as possible and certainly avoid whole-tree harvesting.

In many ways, by simply following the current VFF management standards and the “Twelve Benchmarks for the Health of the Forest,” VFF members are already managing for carbon sequestration. However, we hope that our report emphasizes the necessity of maintaining soil health because soils are such a, essential component of carbon storage.

Certainly it is not essential for VFF members to measure the carbon sequestration occurring on their lands; however, we hope we have shown that it is not at all a difficult process for those who are interested in doing so. Perhaps the most difficult part is the length of time one must wait before being able to make any useful calculations. Gathering simple data on a test plot is not a time-intensive process; however, in order to calculate sequestration the data must be collected again on the same plot after a given amount of time has elapsed. It is possible to collect the data again after only one year, but the resulting figure would not be as useful as waiting 10 years. Information for those interested in calculating carbon sequestration on their lands can be found in Section 3.1.

Annotated Bibliography

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- N fertilized sites had 20% more C in tree biomass compared to unfertilized soils and 48% more soil carbon
- Stands with lower site indices respond better to fertilization, suggesting that some are N limited
- Results were highly variable based on soil origin and texture, but overall N application increased soil C

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- Excellent review article
- Summarizes global soil C budget and synthesizes what we do and do not know about its response to anthropogenic environmental changes of many types.
- Defines/describes soil organic matter
- Describes processes of soil C input/output
- How soil C changes over time and with variations in climate

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Berndes G, Hansson J. 2007. Bioenergy expansion in EU: Cost-effective climate change mitigation, employment creation and reduced dependency of imported fuels. Energy Policy 35: 5965-5979.

Brynn D. 2008. Town Forest Health Check: A town forest steward's guide to forest health assessment. Vermont Family Forest Foundation and UVM's Green Forestry Education Initiative.

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- Study done in a nitrogen-rich area of the Southern Appalachian Mountains in West Virginia
- Found that diameter limit and selective cutting increased carbon sequestration over a 55 year period by 37% as compared to an unmanaged forest
- May not have included coarse woody debris in these calculations, as estimates of carbon sequestration were based on net primary productivity

Dixon RK, Brown S, Houghton RA, Solomon AM, Trexler MC, and Wisniewski J. 1994. Carbon pools and fluxes of global forest ecosystems. Science 263: 185–190.

- Estimates global C pools and fluxes
- Outlines some forest management goals for carbon sequestration

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Hansen K, Vesterdal L, eds. 2004. Planning afforestation on previously managed arable land — influence on deposition, nitrate leaching, and carbon sequestration. Denmark: Forest and Landscape.

- Talks about effect of afforestation on carbon sequestration
- Figure 6 is interesting because it shows the changes in total ecosystem carbon storage with time since afforestation

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Heath LS, Smith JE, Birdsey RA. 2003. Carbon trends in U.S. forestlands: a context for the role of soils in forest carbon sequestration. The Potential of U.S. Forest Soils to Sequester Carbon and Mitigate the Greenhouse Effect. J.M. Kimble, L.S. Heath, R.A. Birdsey, and R. Lal, eds. New York: CRC Press.

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- Excellent diagrams for describing carbon sequestration.

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Honea JM, Vogt KA. 2007. Ecology and conservation of forests. Forests and Society: Sustainability and Life Cycles of Forests in Human Landscapes. Vogt KA, Vogt DJ, Edmonds RL, Honea JM, Patel-Weynand T, Sigurdardottir R, and Andreu MG, eds. Cambridge, MA: CABI International.

- This article clearly defines the difference between gymnosperms and angiosperms and information on nitrogen cycling, water cycling, and other nutrient cycling related to forest ecology. More specifically, this article is related to our study because it discusses the changes that climate change brings to forests. Climate change could bring a warming trend, which will bring warmer evening temperatures and warmer winter temperatures while maintaining the temperature ranges at other times, which would most likely be accompanied by changing precipitation patterns.
- The forest will also experience changes after primary and secondary successions. Primary successions include some type of disturbance that leaves a gap in the forest, such as a felled tree or a forest fire. Primary succession occurs after the organic carbon is removed from the soil. After this disturbance, as more organic matter accumulates in the soil, shade-intolerant plants start to grow, and competition leads the plants to grow taller in height. As the forest becomes established, shade-tolerant species compete in the understory, and since they are able to survive the years needed to grow in the understory, they are able to survive until their height is in the overstory, so shade-tolerant species typically dominate the overstory as well.
- Secondary succession occurs after a less severe event than one that causes a primary succession because secondary succession occurs in a situation where the carbon in the soil is still available. The article goes on to describe the importance of biodiversity for dealing with succession.

IEA Bioenergy. 1998. The role of bioenergy in greenhouse gas mitigation. Retrieved 17 January, 2010 from http://www.ieabioenergy-task38.org/publications/Role%20of%20Bioenergy%20in%20GHG%20Mitigation.pdf

- Excellent article explaining the role of bioenergy
- Describes how greenhouse gases can be mitigated by biomass

Iverson LR, Prasad AM. 1998. Predicting abundance of 80 tree species following climate change in the eastern United States. Ecological Monographs 68(4): 465-485.

- Models range shifts for 80 tree species based on climatic changes
- Tree species composition is predicted to change - sometimes dramatically - in eastern forests. Several tree species, including balsam fir, are expected to shift their southern border into Canada (or close to it).

Jackson RB, Schenk HJ, Jobba EG, Canadell J, Colello GD. Dickinson RE, Field CB, Friedlingstein P, Heimann M, Hibbard K, Kicklighter DW, Kleidon A, Neilson RP, Parton WJ, Sala OE, Sykes MT. 2000. Belowground consequences of vegetation change and their treatment in models. Ecological Applications 10: 470-483.

- discusses how differing treatments of belowground processes influences models of the consequences of vegetation change
- changes in woody and herbaceous vegetation (and the concurrent changes in plant rooting depths) influence the distribution of soil carbon and nutrients over time, as well as the water balance and net primary productivity

Jandl R, Lindner M, Vesterdal L, Bauwens B, Baritz R, Hagedorn F, Johnson D, Minkkinen K, Byrne K. 2007. How strongly can forest management influence soil carbon sequestration? Geoderma 137: 253-268.

- Excellent review of effects of harvesting on soil organic carbon
- All major factors covered: afforestation, tree species, stand management, disturbance, fertilization, site preparation, etc
- General recommendations focus on need for productive forests and minimal soil disturbance

Jandl R, Starlinger f, Englisch M, Herzberger E, Johann E. 2002. Long-term effects of a forest amelioration experiment. Canadian Journal of Forest Research 32: 120-128.

- Evaluation of amelioration work on a site 30 years earlier including fertilization, N-fixing plants, and a combination of both
- Increased growth rate seen for treated soils, both fertilized and underplanted with N-fixing plants
- Carbon pools of treated soils decreased by 20-40%, increased growth rates may compensate for this loss

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Johnson DW, Curtis P. 2001. Effects of forest management on C and N storage: meta analysis. Forest Ecology and Management 140: 227-238.

- Meta analysis was used to determine mean responses of forest soil C and N to different management techniques
- Forest harvesting, on average, had little or no effect on C or N storage, though there were significant effects of different harvesting types
- Examined effects of fire on soil N and C storage. Wildfires led to greater post-fire soil C than prescribed fires.

Johnson KJ, Scatena FN, Pan Y. 2009. Short- and long-term responses of total soil organic carbon to harvesting in a northern hardwood forest. Forest Ecology and Mangement. doi: 10.1016/j.foreco.2009.06.049.

- Two models (CENTURY and YASSO) of soil organic carbon in northern hardwood forests harvested under varying frequencies and intensities over a 360 year period
- Found that only in scenarios of 120 year rotation and 20% biomass removal did soil organic carbon increase from the baseline condition of 80 years of growth following a clear cut
- Unmanaged forest still sequestered more carbon, however, with a 9.9% increase (CENTURY) or a 3.1% increase (YASSO) depending on the model. This is compared to a 0.7% increase (CENTURY) and a 3.2% decrease (YASSO) for 120 year, 20% removal scenario depending on the model used.

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- Estimates soil organic carbon across gradients of temperature and climatic regimes
- Uses isotopes of carbon to estimate turnover time
- Estimates how soil respiration and NPP will change with warming
- Describes linkage between carbon and nitrogen cycles

Klyza CM, Trombulak SC. 1999. The Story of Vermont: A Natural and Cultural History. Hanover, New Hampshire: University Press of New England.

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- Overview of litter decay and the formation of soil organic matter
- Describes the different properties and composition of litter – aboveground and belowground inputs, tissue types of plant residues, plant compounds (lignin, cellulose, tannins, lipids)

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- Excellent overview of carbon in global soils and how it has contributed to and can be used to mitigate anthropogenic climate change
- Breaks down soil C pools by soil orders (density (MT/ac) and total pool of each soil type)
- Describes factors affecting depletion of soil carbon pool and the possible effects of climate change on soil organic matter and quality

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- Overview of global carbon pools and of soils with high carbon sequestration potential (not specific to forest soils)
- Describes potential strategies for soil carbon sequestration
- Explains how soil carbon sequestration relates to soil fertility and, consequently, global food production

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- Review of literature about how forest soils will react to climate change

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- Complete life cycle analysis of carbon sequestration for coniferous plantations and associated wood products
- Trees harvested at maximum sustained yield level can only contain 1/3 as much carbon as a mature stand
- Total carbon in vegetation, soil, and wood products decreased for 10 years after harvest and 5 after thinning (ie plantations were a source), before increasing again as a result of regrowth.
- Effect of increased rotations on total carbon in system variable, but longer rotations (increase from 90 years to 120 years deemed favorable for both Scots pine and Norway spruce due to carbon used in harvest, etc)

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- Describes/defines carbon sequestration and how to convert carbon into biomass.

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- Documented carbon and nitrogen cycling over a decade-long soil warming experiment in a temperate hardwood forest (Harvard Forest)
- Heating the soil led to a loss of approximately 11% of the carbon in the top 60cm of soil over 10 years
- Soil warming leads to both positive and negative feedbacks in the carbon cycle

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- Analysis of carbon sequestration in managed and unmanaged forests
- Found that carbon in managed forest will increase over the next 40 years and then decline
- Carbon stock in unmanaged area will increase for 60 years and then decline
- Total C in the forest following industrial practices will be less than that of a naturally growing forest
- Managing for maximum sustained yield does not necessarily correlate to peak carbon sequestration rates

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- Finds that even when considering carbon sequestered in wood products, unmanaged forests will sequester 28% more carbon than those actively managed
- A shift in management from high intensity, high frequency to low intensity, low frequency can sequester up to 26% more carbon, however, as a result of an emphasis in forest carbon storage instead of wood product storage

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- Includes tables with:carbon storage relative to the baseline for three scenarios of ecological processes on set-aside land (64), and regional gain or loss in carbon relative to the baseline for the years 2010 and 2135 (65).
- Discusses idea of using set-asides for carbon sequestration, which, to my understanding, are plots of lands completely unharvested and unmanaged (61)

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- Definitions of carbon pools in forest ecosystems

Spittlehouse DL, Stewart RB. 2003. Adaptation to climate change in forest management. BC Journal of Ecosystems and Management 4(1): 1-11.

- Provides framework for adaptation in forest management
- Review of possible adaptive actions for forest managers in response to climate change in British Columbia
- Argues that adaptation to climate change in forest management requires a planned response well in advance of the impacts of climate change
- One of the most important things to protect: genetic diversity and resilience of the forest ecosystems

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- Good for overview
- Figure 7.3 - really interesting because shows how long the payback period is in terms of positive GHG benefits. shows that we will want to harvest our wood from lots with certain tonnes of carbon per hectare in order to make a closed look with a shorter time period, but these concentrations of carbon would be extreme, and maybe even impossible.

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- This article succinctly describes the carbon cycle, and it includes the consequences of human actions on the cycle.
- Underscores the importance of balancing carbon sequestration with maintaining a healthy forest and with providing sustainable livelihoods.
- Outlines how photosynthesis enables trees to take in carbon from the atmosphere and converting it to simple sugar carbon compounds in the tree.
- general summary of forest carbon storage and uptake of carbon annually in a young and an old forest
- if we are only looking at live trees for sequestering carbon, we want to have a young stand. However, dead tissues sequester carbon, also.
- describes why carbon accumulates in the soil. Temperature, precipitation, vegetation, and disturbance affect the accumulation and stability of organic matter. Cooler soil conditions, moister soil conditions and improved soil fertility leads to increased organic matter.

Vogt KA, Honea J, Vogt DJ, Andreu M, Edmonds R, Sigurdardottir R, Patel-Waynard T. 2007. Forests and Society: Sustainability and Life Cycles of Forests in Human Landscapes. Cambridge, MA: CABI.

- Discusses young stands versus old-growth forests
- Points out (200) that old-growth forests due sequester more carbon, but this is beyond the time-scale of any human, therefore of human uses of carbon
- Table on chemical components of wood and agricultural crops (203)
- Fig. 6.6 United States CO2 emissions and the proportion that land0use change and forestry provided as a sink in 1990 and 2002 (214).

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- Examined impact of climate change by modeling rise in CO2 concentration, higher temperatures and precipitation, and decrease in nitrogen deposition

- Effects on trees largely depend on species and latitude, but generally an increase in biomass is expected
- Increases in productivity due to higher CO2 levels may be tempered by nutrient limitations
- Areas susceptible to drought may experience decreases in soil CO2, but in general net primary productivity is expected to increase due to climate change, regardless of decreasing nitrogen deposition

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