Quantifying carbon dynamics and sequestration under alternate forest management scenarios in the northern forest: evaluation of sequestration options and tradeoffs

Principal Investigator: William S. Keeton  
Co-Principal Investigator: Jennifer C. Jenkins  
Affiliation: University of Vermont  
Email: william.keeton@uvm.edu  
Mailing address: 343 Aiken Center  
Rubenstein School of Environment and Natural Resources  
University of Vermont  
Burlington, VT 05405  
Collaborator: Jared S. Nunery  
Completion date: Dec. 31, 2009

There are a variety of options available for landowners in the northeastern U.S. that will enhance carbon storage in managed forests, thereby providing opportunities for participation in carbon markets. Collectively, our findings suggest that a shift to less intensive forest management alternatives will result in a net increase in carbon sequestration in northern hardwood ecosystems, so long as the accounting is restricted to forest and wood products carbon pools.

Funding support for this project was provided by the Northeastern States Research Cooperative (NSRC), a partnership of Northern Forest states (New Hampshire, Vermont, Maine, and New York), in coordination with the USDA Forest Service.  
http://www.nsrcforest.org
Temperate forests are an important carbon sink, yet there is debate regarding the net effect of forest management practices on carbon storage. Few studies have investigated the effects of different silvicultural systems on forest carbon stocks, and the relative strength of *in-situ* forest carbon versus wood products pools remains in question. Our research (1) described the impact of harvesting frequency and proportion of post-harvest structural retention on carbon storage in northern hardwood-conifer forests, and (2) tested the significance of including harvested wood products in carbon accounting at the stand scale. We stratified Forest Inventory and Analysis (FIA) plots to control for environmental, forest structural and compositional variables, resulting in 32 FIA plots distributed throughout the northeastern U.S. We used the USDA Forest Service’s Forest Vegetation Simulator to project stand development over a 160 year period under nine different forest management scenarios. Simulated treatments represented a gradient of increasing structural retention and decreasing harvesting frequencies, including a “no harvest” scenario. The simulations incorporated carbon flux between aboveground forest biomass (dead and live pools) and harvested wood products. Mean carbon storage over the simulation period was calculated for each silvicultural scenario. We investigated tradeoffs among scenarios using a factorial treatment design and two-way ANOVA. Mean carbon sequestration was significantly ($\alpha = 0.05$) greater for “no management” compared to any of the active management scenarios. Of the harvest treatments, those favoring high levels of structural retention and decreased harvesting frequency stored the greatest amounts of carbon. Classification and Regression Tree analysis showed that management scenario was the strongest predictor of total carbon storage, though site-specific variables were important secondary predictors. In order to isolate the effect of *in-situ* forest carbon storage and harvested wood products, we did not include the emissions benefits associated with substituting wood fiber for other construction materials or energy sources. Modeling results from this study show that harvesting frequency and structural retention significantly affect mean carbon storage. Our results illustrate the importance of both post-harvest forest structure and harvesting frequency in carbon storage, and are valuable to land owners interested in managing forests for carbon sequestration.
Developing carbon markets have recognized the important role of forests in the terrestrial C cycle and the potential contribution of sustainable forest management to climate change mitigation efforts. A working hypothesis is that “improved forest management” could achieve higher levels of C storage (termed “additionality”) compared to “business as usual” or a baseline condition. While forest management clearly impacts terrestrial carbon storage, little information is available describing how specific forest management alternatives might affect C storage and sequestration. This understanding is vital, because the dynamics of storage and fluxes among the different sinks impacted by management (e.g. forest C versus wood products pools) are complex, rendering accounting of net effects on C storage challenging. The purpose of this study was to inform forest C management practices using empirical data coupled with forest-stand development modeling. We investigated the impacts of harvesting frequency and post-harvest retention on C sequestration in managed forests in the northeastern U.S. We also specifically address the importance of accounting for C stored in wood products when determining net effects on sequestration.

Some researchers have suggested that sustainably managed forests sequester more C than unmanaged forests, stressing the high tree growth rates achieved in harvested stands, and C stored in wood products. However, other studies have demonstrated that unmanaged forests sequester greater amounts of C than managed forests. A series of studies have shown that intensified forest management actually leads to a net flux of C to the atmosphere due to lower biomass in harvested stands and the often short lifespan of wood products. These conclusions, however, are based primarily on studies involving conversion of old-growth forest to young plantations and the effects of intensive harvesting practices, such as clearcutting. Net effects on C dynamics across a range of silvicultural systems, including modified even-aged and less intensive uneven-aged forest management practices, remain poorly explored and thus were a focus of this study.

Our study addressed a fundamental research question facing forest managers, namely: what is the most effective way to store C through forest management? Is C sequestration greater under more intensive approaches favoring high rates of uptake and C transfer to wood products? Or are less intensive approaches, favoring in-situ forest C storage, more effective at maximizing C storage? We tested two key variables with the potential to affect forest C sequestration: 1) harvesting frequency (rotation length or entry cycle), and 2) post-harvest structural retention (residual biomass following a harvest). We hypothesized that silvicultural prescriptions with increased structural retention coupled with decreased harvesting frequency would sequester the greatest amount of C relative to other active management scenarios.
Forest Carbon Accounting: Scales of Analysis

Red circles = C pools investigated in this study
Considering in-situ carbon and wood products, what is more effective?

- Intensified forest harvests, favoring fast rates of uptake and storage in wood products?

- Reduced harvesting intensity/frequency and/or passive management (reserves) favoring carbon storage in extant forests?
Background

Aboveground Live Biomass

Standing Dead Wood

Coarse Woody Debris
Background

Greatest level of carbon sequestration

Greatest rate of carbon uptake

Stand development over time
Methods

- The geographic focus of this study was the northern hardwood region of the northeastern U.S., encompassing portions of upstate New York, Vermont, New Hampshire, and Maine.
- We stratified Forest Inventory and Analysis (FIA) plots to control for environmental, forest structural and compositional variables, resulting in 32 FIA plots distributed throughout the northeastern U.S.
- We used the USDA Forest Service’s Forest Vegetation Simulator to project stand development over a 160 year period under nine different forest management scenarios.
- Simulated treatments represented a gradient of increasing structural retention and decreasing harvesting frequencies, including a “no harvest” scenario. The simulations incorporated carbon flux between aboveground forest biomass (dead and live pools) and harvested wood products. Mean carbon storage over the simulation period was calculated for each silvicultural scenario.
- We investigated tradeoffs among scenarios using a factorial treatment design and two-way ANOVA.
- The relative predictive strength of management scenarios vs. site-specific factors was evaluated using multivariate statistical approaches (Classification and Regression Trees).
Stratified random sample of FIA sites

32 stands from the Northern Forest Region

14 stands from the White Mountains and western Maine

3 stands from the Green Mountain Region

15 stands from the Adirondack Region

http://www.na.fs.fed.us/sustainability/ecomap/eco.sh
Forest Vegetation Simulator

- Use regional growth and yield equations (developed by NE-TWIGS)
- Not spatially explicit
- Individual tree growth model
- Designed for both even and uneven aged stands of mixed species composition
- Regeneration is an input parameter
- Carbon derived from species-specific allometric equations
- Wood product carbon based on US Forest Service research

http://www.fs.fed.us/fmsc/fvs/variants/index.shtml
Methods: Management scenarios

8 active management scenarios across a gradient of harvesting intensity and frequency

Clearcut (2)  
Shelterwood (2)  
Single tree selection system (ITS) (4)
<table>
<thead>
<tr>
<th>Even-aged Silvicultural Prescriptions</th>
<th>Rotation Length</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Short (80 years)</td>
<td></td>
<td>Long (120 years)</td>
</tr>
<tr>
<td></td>
<td>1) Commercial thin: implement when stand reaches stocking density above normal.</td>
<td>1) Commercial thin: implement when stand reaches stocking density above normal.</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>2) <strong>Clearcut: 2005 and 2085</strong> -No legacy trees</td>
<td>2) <strong>Clearcut: 2005 and 2125</strong> -No legacy trees.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>*Whole tree harvest</td>
<td></td>
<td>*Whole tree harvest</td>
</tr>
<tr>
<td>High</td>
<td>1) Commercial thin: implement when stand reaches stocking density above normal.</td>
<td>1) Commercial thin: implement when stand reaches stocking density above normal.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2) <strong>Shelterwood: 2005 and 2085</strong> -residual BA 60ft²/ac -15 legacy TPA, smallest diameter in removal cut 6 in</td>
<td>2) <strong>Shelterwood: 2005 and 2125</strong> -residual BA 60ft²/ac -15 legacy TPA, smallest diameter in removal cut 6 in.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>*Slash left on site</td>
<td></td>
<td>*Slash left on site</td>
</tr>
<tr>
<td>Uneven-aged Silvicultural Prescriptions</td>
<td>Residual Structure</td>
<td>Entry Cycle Length</td>
<td>Entry Cycle Length</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>-------------------</td>
<td>--------------------</td>
<td>--------------------</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>Short (15 years)</td>
<td>Long (30 years)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Entry Cycle Length: 15 yrs</td>
<td>Entry Cycle Length: 30 yrs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q-value: 1.3</td>
<td>Q-value: 1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual BA: 65 ft²/ac</td>
<td>Residual BA: 65 ft²/ac</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min DBH Class: 2 in</td>
<td>Min DBH Class: 2 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max DBH Class: 20 in</td>
<td>Max DBH Class: 20 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBH Class Width: 2 in</td>
<td>DBH Class Width: 2 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of Legacy TPA: 0</td>
<td>Number of Legacy TPA: 0</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>Entry Cycle Length: 15 yrs</td>
<td>Entry Cycle Length: 30 yrs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Q-value: 1.3</td>
<td>Q-value: 1.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Residual BA: 85 ft²/ac</td>
<td>Residual BA: 85 ft²/ac</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min DBH Class: 2 in</td>
<td>Min DBH Class: 2 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max DBH Class: 24 in</td>
<td>Max DBH Class: 24 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DBH Class Width: 2 in</td>
<td>DBH Class Width: 2 in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Number of Legacy TPA: 5</td>
<td>Number of Legacy TPA: 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Average legacy tree diameter: 16 in</td>
<td>Average legacy tree diameter: 16 in</td>
</tr>
</tbody>
</table>
Results

- Mean carbon sequestration was significantly ($\alpha = 0.05$) greater for “no management” compared to any of the active management scenarios.
- Of the harvest treatments, those favoring high levels of structural retention and decreased harvesting frequency stored the greatest amounts of carbon.
- Even with consideration of C sequestered in harvested wood products, unmanaged northern hardwood forests will sequester a minimum of 39% more C than any of the active management options evaluated.
- A shift from high frequency management with low structural retention to low frequency management with high structural retention can sequester up to 57% more C. Less dramatic alteration of silvicultural practices can still create additionality of approximately 20%. These differences are largely a result of the significant initial loss of C incurred from removal of large quantities of C stored in live and dead aboveground tree biomass, slow post-harvest accretion of C in dead wood pools, and the transient nature of C in the wood products stream.
- Management scenario was the strongest predictor of total carbon storage, though site-specific variables were important secondary predictors.
- In order to isolate the effect of in-situ forest carbon storage and harvested wood products, we did not include the emissions benefits associated with substituting wood fiber for other construction materials or energy sources.
- Modeling results from this study show that harvesting frequency and structural retention significantly affect mean carbon storage.
Nunery and Keeton, in preparation.

Key:
- CH = Clearcut, high frequency
- CL = Clearcut, low frequency
- SH = Shelterwood, high frequency
- SL = Shelterwood, low frequency
- ITS_LH = Selection, low retention, high frequency
- ITS_LL = Selection, low retention, low frequency
- ITS_HH = Selection, high retention, high frequency
- ITS_HL = Selection, high retention, low frequency
- NM = No management

Management scenario

Carbon (metric tons per hectare)

- Purple: C storage in harvested wood products
- Green: Coarse woody debris
- Red: Standing dead
- Blue: Aboveground live biomass
CART model: Mean total carbon $\sim f$ (Scenario, Ecoregion, Site Index, Aspect, Percent Conifer, Basal Area, Quadratic Mean Diameter, Structure Class, Number of strata, Slope, Stand age). $N = 288$
Implications and applications in the Northern Forest region

- Options for increasing net carbon storage in northern hardwood forests include:
  - Longer rotations or entry cycles
  - Increased post-harvest retention of live and dead trees
  - Increased emphasis on production of durable wood products
  - Modified silvicultural approaches that promote structural complexity and high in-situ forest biomass
  - Passive management: reserves that will develop high levels of biomass

- FVS simulations: less intensive management and longer rotations consistently yield higher average carbon storage over multiple rotations/entries.
  - This analysis includes forest carbon and wood products, but does not include biomass fuel or product substitutions.
  - Inclusion of biomass fuel offsets and substitution effects increase the net carbon benefit of more intensive management scenarios.
Future directions

• Our future work will explore the net carbon emissions and offsets associated with forest biomass energy production and utilization

• These represent an important element of carbon accounting, expanding upon the results reported in this study
List of products

Journal Papers:


Graduate Thesis:


Reports:

Invited Presentations to Date:

Keeton, W.S. Forest carbon management alternatives for the northern forest. Vermont Land Trust board meeting. Dec. 11, 2009, Burlington, VT.


Keeton, W.S. Biomass and carbon storage in old-growth temperate forests: implications for forest carbon management. Invited seminar at Univeritat fur Bodenkulture (University of Natural Resources and Applied Life Sciences), Institute for Forest Ecology. April 28, 2009, Vienna, Austria.


Contributed Presentations to Date:


Keeton, W.S. Biomass development in riparian late-successional northern hardwood-hemlock forests: implications for forest carbon sequestration and management. Ecological Society of America 93rd Annual Conference. August 3-8, 2008, Milwaukee, WI.