Factors controlling carbon sequestration at Howland Forest, Maine: Long-term trends, interannual variability, and forest management impacts

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Overview

• Why care about carbon sequestration?
• Long-term trends in carbon sequestration in unmanaged forest
• Effects of shelterwood harvest on carbon sequestration
• Can a shelterwood regime enhance carbon sequestration?
Howland Forest

- Commercial spruce-hemlock forest
  - GMO Renewable Resources LLC (formerly IP)
- LAI ~5.5
- Live tree C ~110 t C ha\(^{-1}\)
- BA ~43 m\(^2\) ha\(^{-1}\)
- Age ~140 years
Interannual variability in carbon uptake

- Interannual variability of forest C sequestration is high (if you do an experiment you need a control!)

Harvard forest data courtesy S. Wofsy
• Reconstructed diameters indicate a mean tree sink of 164 g C m\(^{-2}\) y\(^{-1}\)
• Uptake decreasing by 1 g m\(^{-2}\) y\(^{-1}\)

- Tree C sink not correlated with variations in tower flux, but consistent with tower data
Modeling net ecosystem carbon exchange

\[ NEE = R_{max} e^{-\frac{E_0}{(246-T_a)}} + \frac{P_{max} I}{K_m + I} + A e^{-\frac{E_a}{(T_{soil}-T_0)}} \]

Annual predictions require carbon pool information!
Howland AmeriFlux Site

Nitrogen addition experiment (1999-)

Long-term flux studies (1996 - )

Ikonos imagery courtesy M. Martin, UNH EOS

Shelterwood Harvest
Jan. 2002

+18 kg N ha\(^{-1}\) y\(^{-1}\)
Changes in forest management practices in Maine (1994-1999)

Total harvested area in 1999: 536,219 acres (6% increase from 1994)

Shelterwood system – 2-3 harvests, 5-15 years apart, enhances natural conifer regeneration
How forest management alters carbon sequestration:

- Affects age structure
- Modify carbon distribution in the forest (e.g. more dead wood)
- Change in soil C:N ratio
- Changes in carbon allocation within trees (e.g. leaves vs. roots vs. stems)
- Can change stand structure (light interception)
- Can change growth efficiency (linked to changes in age-structure, nutrient availability)
- Types of wood influences types of products
Shelterwood harvest

Started Nov. 2001
Ended April 2002
Cut to length and forwarded
Removed about 1/3 of basal area and leaf area

Photo courtesy of Mary Martin
The impact of a harvest on forest C sequestration depends on several things:

- What happens to C uptake & loss in the remaining forest?
  - How does photosynthesis change? Compensation?
  - How does soil respiration change? Reduction?
- How much slash is produced & how quickly does it decay?
  - Belowground versus aboveground losses
- How much wood is removed and what is its fate?
### Carbon pools and harvest C fluxes:

<table>
<thead>
<tr>
<th>Carbon pool</th>
<th>Control</th>
<th>Harvested (pre-)</th>
<th>Harvest C fluxes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Live basal area (m² ha⁻¹)</td>
<td>43 (2.4)</td>
<td>30 (1.7)</td>
<td>22</td>
</tr>
<tr>
<td>Live biomass (t C ha⁻¹)</td>
<td>109 (6.6)</td>
<td>77.3 (4.7)</td>
<td></td>
</tr>
<tr>
<td>Standing dead (t C ha⁻¹)</td>
<td>10.8 (1.2)</td>
<td>3.3 (0.8)</td>
<td></td>
</tr>
<tr>
<td>Down-dead (t C ha⁻¹)</td>
<td>4.1</td>
<td>16.1 (3.9)</td>
<td></td>
</tr>
<tr>
<td>Soil</td>
<td>110</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood removal (t C ha⁻¹)</td>
<td></td>
<td></td>
<td>14.9 (2.1)</td>
</tr>
<tr>
<td>AG detritus (t C ha⁻¹)</td>
<td></td>
<td></td>
<td>5.3 (1.1)</td>
</tr>
<tr>
<td>BG detritus (t C ha⁻¹)</td>
<td></td>
<td></td>
<td>5.2 (0.7)</td>
</tr>
</tbody>
</table>
Detritus production and decay (II)

Dead wood respiration is related to temperature...

\[
\text{Ln respiration} = 0.092\text{Temp} - 0.014; \quad R^2 = 0.21
\]

Result: Half life ~ 2.5 years

...but also to water content
Soil respiration in harvested and control stands

Respiration rates lower after harvest (2003 and 2004)
Impact of harvest on net carbon exchange

To examine the impact of harvest on net C flux, we compared fluxes from the control and harvested tower both pre- and postharvest

Preharvest slope (2001) = 0.92
Postharvest slope (2002) = 0.75
Postharvest slope (2004) = 0.89

Suggest an initial 18% reduction in net C storage as a result of harvest (30% BA removed) but then a recovery.
Impact of harvest on carbon uptake efficiency (growing season)

Whole stand:
Drops then recovers

Per unit BA:
Slight drop and then big increase by 3$^{rd}$ year

Control: 1.99 Mg C ha$^{-1}$ y$^{-1}$ (95% CI=0.5)

Harvested: 1.79 Mg C ha$^{-1}$ y$^{-1}$ (95% CI=0.5)
Simulated carbon losses following harvest (with and without wood products)

Without harvest: 54 Mg C ha\(^{-1}\) (30y)
With harvest, assuming no enhanced uptake: 34 Mg C ha\(^{-1}\) (30y)
With harvest, 40% enhancement in net uptake: 54 Mg C ha\(^{-1}\) (30y)

Measured net uptake for 2004 = 0.70 ± 0.25 t C ha\(^{-1}\)y\(^{-1}\)
Summary

• Mature, relatively undisturbed forests at Howland, Maine sequester about 1.9 t C ha\(^{-1}\) y\(^{-1}\), primarily in bole wood

• Shelterwood harvest removed about 30% of stand biomass, and created detritus containing \(~10\ t\ C\ ha\(^{-1}\)

• Soil respiration is lower two years after harvest, and respiration from slash is strongly related to BOTH temperature and moisture content

• Simulated net C uptake 3 years after harvest (0.6 t C ha\(^{-1}\) y\(^{-1}\)) agrees closely with measured net uptake (0.7 t C ha\(^{-1}\) y\(^{-1}\)) that year - **Strong Growth Enhancement in the Remaining Trees**

This research was supported by Office of Science (BER), US Department of Energy under Interagency Agreement No. DE-AI02-00ER63028 to the USDA Forest Service, by Grant No. DE-FG02-00ER63002 to WHRC and DE-FG02-00ER63001 to U. Maine and by the USDA Forest Service NE Research Station.
Site age from land use reconstruction:

- Near navigable river, flat land → Colonial use
- Charcoal in soil → Site burned
- Soil horizons intact → Not plowed, grazed
- Age synchrony → Pasture abandoned

~1860, forest age 140

Old for eastern US
Fate of harvested wood:
Wood products produced, and their longevity, affects the net C balance of the shelterwood harvest regime

<table>
<thead>
<tr>
<th>Product</th>
<th>Wet mass (tons)</th>
<th>% total</th>
<th>Half-life (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boltwood</td>
<td>232</td>
<td>2</td>
<td>20</td>
</tr>
<tr>
<td>Chipwood</td>
<td>364</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>Groundwood</td>
<td>199</td>
<td>2</td>
<td>3.5</td>
</tr>
<tr>
<td>Logs</td>
<td>4771</td>
<td>40</td>
<td>45</td>
</tr>
<tr>
<td>Pulp</td>
<td>4265</td>
<td>36</td>
<td>3.5</td>
</tr>
<tr>
<td>Studs</td>
<td>463</td>
<td>4</td>
<td>45</td>
</tr>
<tr>
<td>‘Tree length’</td>
<td>1511</td>
<td>13</td>
<td>3.5</td>
</tr>
</tbody>
</table>

Carbon consequences of forest management

Photosynthesis → CO₂ → Respiration → CO₂ → Photosynthesis

Reduced Photosynthesis → CO₂ → Increased Respiration → CO₂ → Reduced Photosynthesis

Forest regrowth

Harvest

CO₂

Debris

Forest products

Timber

Paper products

Wood products

Sawdust

How quickly does forest growth recover?
Factors influencing Forest C Sequestration:

- Historical land-use (age structure and (perhaps) growth rates)
- Climate Change (season length, precipitation)
- CO\textsubscript{2} fertilization
- Nitrogen deposition

- Forest use/management
  - Current land-use assessments include logging (clear-cutting and regrowth), fire suppression, cropland, pasture (Houghton et al. 1997).
  - Subtle management practices not included (e.g. thinning, low-intensity logging; lead to changes in species composition, carbon distribution in ecosystem pools).
Impact of harvest on net carbon exchange (I)

**Initial predictions**
- Decreased uptake
- Increased respiration

**Ecosystem Exchange Characteristics**

<table>
<thead>
<tr>
<th></th>
<th>Control Tower μmol m$^{-2}$ s$^{-1}$ (mean ± std dev, n)</th>
<th>Harvest Tower μmol m$^{-2}$ s$^{-1}$ (mean ± std dev, n)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>6 months postharvest</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day</td>
<td>-9.3 ± 5.1, n=502</td>
<td>-5.9 ± 5.7, n=490</td>
</tr>
<tr>
<td>Night</td>
<td>5.5 ± 4.0, n=497</td>
<td>3.0 ± 4.8, n=506</td>
</tr>
<tr>
<td><strong>30 months post</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Day</td>
<td>-7.6 ± 7.8, n=711</td>
<td>-6.4 ± 7.7, n=538</td>
</tr>
<tr>
<td>Night</td>
<td>6.0 ± 3.0, n=277</td>
<td>6.9 ± 4.0, n=191</td>
</tr>
</tbody>
</table>
Flux data show that forests can switch between sink & source depending on weather.

- Mean uptake $188 \text{ g C m}^{-2} \text{ y}^{-1}$
- High variability
- Uncertainty $\sim 20 \text{ g C m}^{-2} \text{ y}^{-1}$