Carbon Sequestration in Northern Great Lakes Forests

Christopher M. Gough[1]*, Christoph S. Vogel[2], Hans Peter Schmid[3], Hong-Bing Su[4] and Peter S. Curtis[1]

[1]The Ohio State University, Department of Evolution, Ecology and Organismal Biology, Columbus, OH 43210, *gough.21@osu.edu;
[2]The University of Michigan, Biological Station; [3]Indiana University, Department of Geography; [4]East Carolina University, Department of Geography

This research was supported by the Office of Science (BER), U.S. Department of Energy, through the Midwestern Regional Center of the National Institute for Global Environmental Change under Cooperative Agreement No. DE-FC03-90ER61010.

1.Overview and Objectives

Forests of the northern Great Lakes, comprising over 12 million hectares, represent a substantial North American carbon stock. Carbon sequestration by these ecosystems can be estimated from ecological inventories and from meteorological measurements. Conceptually, these approaches should provide equivalent measures (Fig. 1) but there are significant uncertainties associated with both methods. Concurrent ecological and meteorological measurements allow for methodological cross-validation and improved regional carbon sequestration estimates.

Objectives:

1. To assess annual and cumulative carbon sequestration in a northern deciduous forest.
2. To compare carbon sequestration estimates calculated from ecological inventory and meteorological data.
3. To partition carbon taken up by the forest into specific above- and belowground pools.

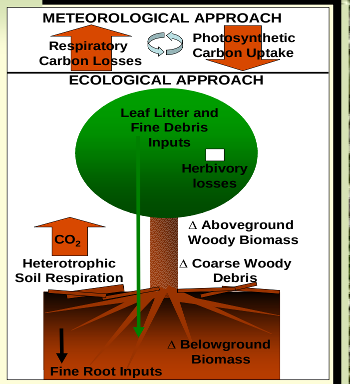
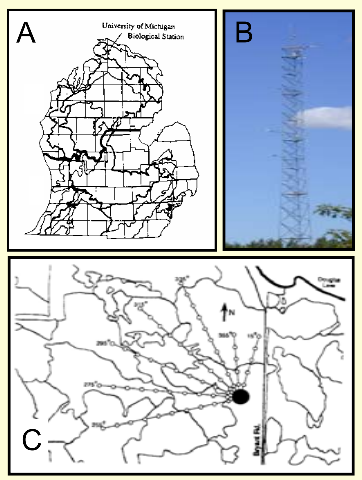


Figure 1. Conceptual diagram showing the carbon fluxes included in carbon sequestration estimates.

2. Study Site and Methods



Our study was conducted at the University of Michigan Biological Station (45º35'N, 84º42'W, Fig 2A). Mean annual temperature and precipitation are 5.5ºC and 817 mm, respectively. The 85-yr-old mixed deciduous forest is dominated by bigtooth aspen (*Populus grandidentata*) and oak/maple species. Canopy height is approximately 20 m. The forest was harvested and burned in the early 20th century. Soils are well drained spodosols.

Figure 2. Study site location in northern lower Michigan (A). Carbon sequestration was estimated using a 46 m meteorological tower and eddy-covariance flux measurement systems (B) and from ecological inventories conducted in plots near the flux tower. Ecological inventory plots were placed within the flux tower footprint to the northwest (C).

3. Carbon Sequestration: Meteorological Results

Annual carbon sequestration estimated from meteorological data averaged 1.51 Mg C ha^{-1} yr^{-1} from 1999 - 2003.

The forest was a net carbon source until late Spring when photosynthetic carbon uptake exceeded respiratory carbon losses. Cumulative, year-end carbon sequestration estimated from meteorological data (annual $C\text{-}seq_M$) ranged from 0.80 to 1.77 Mg C ha^{-1} yr^{-1}.

Cumulative Carbon Sequestration by the UMBS Forest

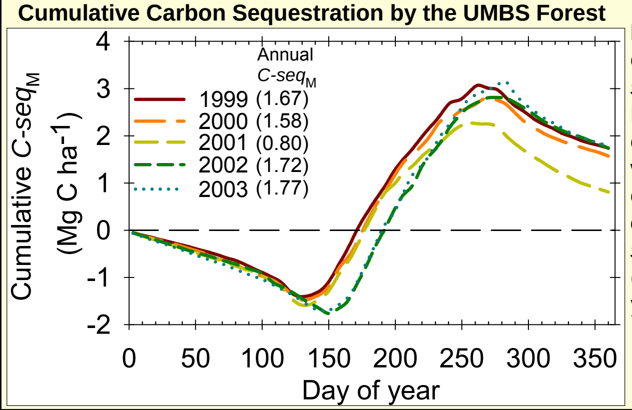


Figure 3. Cumulative forest carbon sequestration ($C\text{-}seq_M$) at UMBS, 1999-2003. Positive fluxes represent carbon uptake by the forest while negative fluxes indicate carbon loss. Annual $C\text{-}seq_M$, or year-end cumulative $C\text{-}seq_M$, is also presented (Annual $C\text{-}seq_M$ = Mg C ha^{-1} yr^{-1}).

4. Carbon Sequestration: Ecological Results

Annual carbon sequestration estimated from ecological data averaged 1.53 Mg C ha^{-1} yr^{-1}. Nearly half of the carbon was stored in roots, reinforcing the importance of belowground pools in forest carbon storage.

Table 1. Partitioned and total annual forest carbon sequestration calculated from ecological inventories, 1999-2003. Living mass increment (ΔL) is the sum of above- (ΔM_a) and belowground (ΔM_b) woody mass increment. Detritus mass increment (ΔD) is the sum of leaf (ΔM_{ll}), fine and coarse woody debris (ΔM_{fd+cd}), and fine root detritus mass increment (ΔM_{fr}). Foliar losses to herbivory (ΔH) and soil heterotrophic respiration (R_h) are also presented. $C\text{-}seq_E$ is the sum of ΔL, ΔD, ΔH and R_h. Standard errors are in parentheses. All units are in Mg C ha^{-1} yr^{-1}, except 5-yr totals.

Year	ΔL		ΔD			ΔH[5]	R_h[6]	$C\text{-}seq_M$
	ΔM_a[1]	ΔM_b[1]	ΔM_{ll}[2]	ΔM_{fd+cd}[3]	ΔM_{fr}[4]			
1999	1.51 (0.18)	0.35 (0.04)	1.42 (0.12)	0.20 (0.29)	3.00 (0.58)	0.06 (0.01)	-5.58 (0.95)	0.96 (1.24)
2000	1.82 (0.08)	0.42 (0.02)	1.60 (0.13)	0.16 (0.29)	2.67 (0.41)	0.06 (0.01)	-4.94 (0.86)	1.79 (1.06)
2001	2.09 (0.07)	0.48 (0.02)	1.44 (0.12)	0.15 (0.29)	2.75 (0.44)	0.10 (0.01)	-5.03 (0.85)	1.98 (1.09)
2002	1.46 (0.05)	0.33 (0.01)	1.52 (0.15)	0.16 (0.29)	2.54 (0.40)	0.06 (0.01)	-4.73 (0.80)	1.34 (1.04)
2003	1.75 (0.11)	0.40 (0.03)	1.48 (0.14)	0.18 (0.29)	2.49 (0.45)	0.06 (0.01)	-4.80 (0.82)	1.56 (1.07)
Total	8.63 (0.49)	1.98 (0.12)	7.46 (0.66)	0.85 (1.45)	13.45 (2.28)	0.34 (0.05)	-25.08 (4.28)	7.63 (5.50)
Mean	1.73 (0.16)	0.40 (0.02)	1.49 (0.13)	0.17 (0.29)	2.69 (0.46)	0.07 (0.01)	-5.02 (0.86)	1.53 (1.10)

1. ΔM_a, ΔM_b were estimated from species-specific allometric equations that relate diameter at breast height (dbh) to woody mass.
2. ΔM_{ll} was calculated from litter traps located on the forest floor.
3. ΔM_{fd+cd} was calculated from litter traps and coarse woody debris censuses.
4. ΔM_{fr} was estimated using three approaches: (1) an empirical site-specific model relating fine root turnover to mean annual soil temperature, (2) a model relating nitrogen mineralization to fine root turnover and (3) a mass balance approach.
5. ΔH was estimated from leaf area surveys following insect infestation and insect feeding trials.
6. R_h was estimated from soil CO_2 efflux measurements and a simple partitioning of heterotrophic and autotrophic respiration.

5. Comparing the Carbon Sequestration Estimates

The two forest carbon sequestration estimates differed considerably on an annual basis, but converged to within 1% of each other over 5 years.

Annual Carbon Sequestration

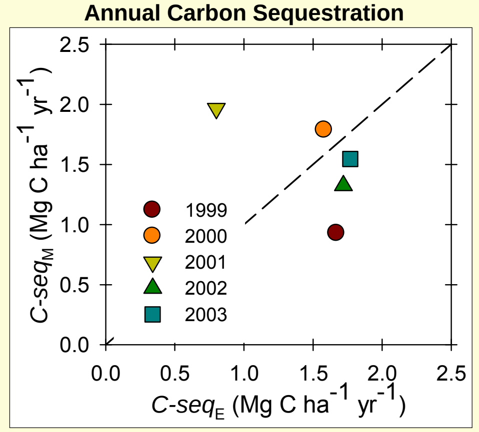


Figure 4. Annual carbon sequestration estimated from ecological data ($C\text{-}seq_E$) and meteorological data ($C\text{-}seq_M$) for the UMBS forest, 1999-2003. Dashed line illustrates the 1:1 relationship.

- **$C\text{-}seq_B$ and $C\text{-}seq_M$ differed from each other by 13 – 148 % when compared on an annual timescale.**

5 Year Carbon Sequestration

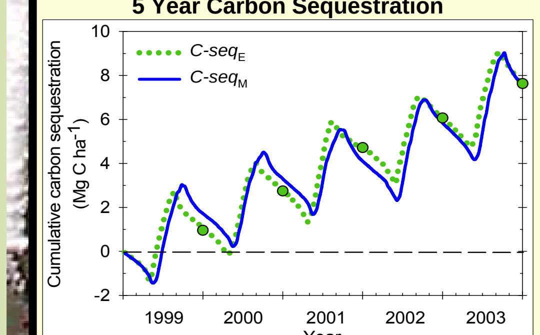


Figure 5. Cumulative 5-yr carbon sequestration based on ecological ($C\text{-}seq_E$) and meteorological ($C\text{-}seq_M$) measurements.

- **Agreement between cumulative $C\text{-}seq_E$ and $C\text{-}seq_M$ improved considerably over time, differing by 74, 18, 17, 5 and 1 % after 1, 2, 3, 4 and 5 yrs, respectively. Cumulative $C\text{-}seq_E$ and $C\text{-}seq_M$ were 7.54 and 7.63 Mg C ha^{-1}, respectively, after 5 years.**

6. Carbon Storage Lags Canopy Carbon Uptake

Agreement between the two estimates is poor on an annual scale because of a seasonal lag between photosynthesis and growth.

Seasonal Trends in Photosynthesis and Growth

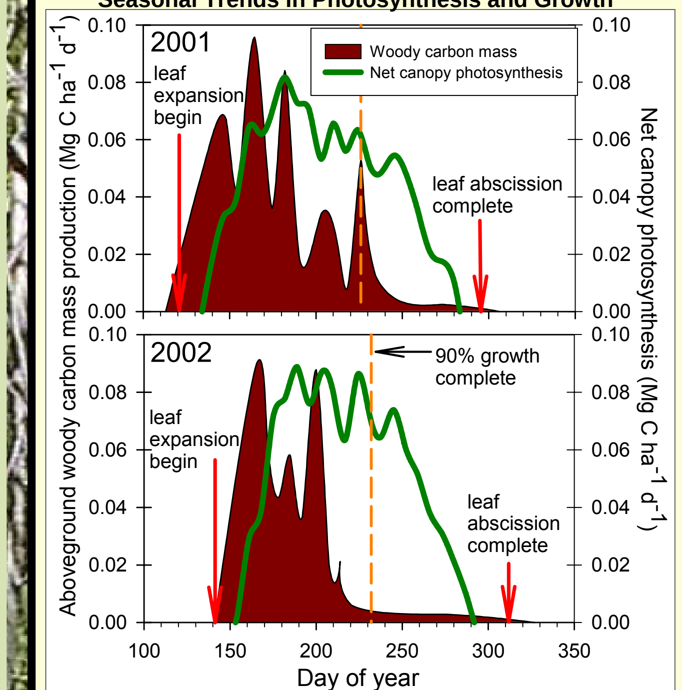


Figure 6. Aboveground woody carbon mass production and net canopy photosynthesis during the 2001 and 2002 growing seasons. Vertical dashed line indicates the date on which 90 % of the total cumulative woody growth was achieved (2001 = day 226; 2002 = day 232).

- Woody growth and leaf expansion began prior to positive net photosynthesis in 2001 and 2002.
- More than 1/4 of the photosynthetic carbon uptake occurred after growth had stopped:
  - 1.86 Mg C ha^{-1} or 26% of annual total in 2001
  - 2.37 Mg C ha^{-1} or 30% of annual total in 2002
- Growth was greater in 2003 than in 2002, and paralleled late-season canopy photosynthesis patterns in 2001 and 2002.
- **These data suggest that carbon taken up via photosynthesis late in the growing season was stored over winter and applied to growth the following year. This lag between processes helps explain the poor agreement between ecological and meteorological estimates of annual forest carbon sequestration.**

7. Validation of Carbon Sequestration Estimates

- **Annual carbon sequestration by the UMBS forest is similar to other deciduous forests in the region, averaging 1.52 Mg C ha^{-1} yr^{-1}, but varying interannually by >100 %.**
- **Ecological and meteorological estimates of forest carbon sequestration converged to within 1% of each other over 5 years, providing an important cross-validation of these independent estimates (Fig. 5). These results indicate that both techniques can provide accurate estimates of carbon sequestration in these forests.**

8. Regional Carbon Sequestration

- **A first approximation suggests that the 12.5 million hectares of deciduous forestland in the northern Great Lakes sequester ~19 Tg of C per year[1].**
- **This is equivalent to ~12 % of the 106 Tg C currently emitted per year by anthropogenic sources in the upper Great Lakes region[2].**
- **Regional inventories suggest that reforestation of abandoned agricultural fields could increase future forest carbon sequestration in the northern Great Lakes. However, other variables including forest age, disturbance history, and future climate must be considered.**

[1]Based on average annual forest carbon sequestration rates (this study) and USDA Forest Inventory and Analysis data (2003) for Michigan, Minnesota and Wisconsin. Includes all forest types represented in the UMBS meteorological tower footprint.
[2]Based on DOE data for 2003 fossil fuel CO_2 emissions in Michigan, Minnesota and Wisconsin.