Detection of long-term trends in carbon accumulation by forests in Northeastern U. S. and determination of causal factors

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Introduction

The overall project goal was to quantify the trends and variability for Net ecosystem exchange of CO_2, H_2O, and energy by northeastern forests, with particular attention to the role of succession, differences in species composition, legacies of past land use, and disturbances. Measurements included flux measurements and observations of biomass accumulation using ecosystem modeling as a framework for data interpretation.

Continuation of the long-term record at the Environmental Measurement Site (EMS) Tower was a priority. The final quality-assured CO_2-flux data now extend through 2010. Data through 2011 are collected but not yet finalized. Biomass observations on the plot array centered on the tower are extended to 2011. Two additional towers in a hemlock stand (HEM) and a younger deciduous stand (LPH) complement the EMS tower by focusing on stands with different species composition or age distribution and disturbance history, but comparable climate and soil type.

Over the period since 1993 the forest has added 24.4 Mg-C ha^{-1} in the living trees. Annual net carbon uptake had been increasing from about 2 Mg-C $ha^{-1}y^{-1}$ in the early 1990s to nearly 6 Mg-C $ha^{-1}y^{-1}$ by 2008, but declined in 2009-2010. We attribute the increasing carbon uptake to a combination of warmer temperatures, increased photosynthetic efficiency, and increased influence by subcanopy hemlocks that are active in the early spring and late autumn when temperatures are above freezing but the deciduous canopy is bare. Not all of the increased carbon accumulation was found in woody biomass. Results from a study using data to optimize parameters in an ecosystem process model indicate that significant changes in model parameters for photosynthetic capacity and shifts in allocation to slow cycling soil organic matter are necessary for the model to match the observed trends. The emerging working hypothesis is that the pattern of increasing carbon uptake over the early 2000's represents a transient pulse that will eventually end as decomposition of the accumulated carbon catches up.

Research highlights

Carbon uptake trends The signature result from the long-term flux measurements at the Harvard Forest tower is the apparent trend towards increasing carbon uptake (Figure 1). From 1992 to 2008 the magnitude of annual NEE increased from about 2 Mg-C $ha^{-1}y^{-1}$ to nearly 6 Mg-C $ha^{-1}y^{-1}$, but has declined over the final two years in the record. Over this same period the accumulation of woody biomass represented by AGWI=above-ground wood increment (dbh>10cm) increased but generally lagged the annual NEE by a year. Likewise, aboveground net primary productivity (ANPP), which combines wood and litter production has generally tracked the annual NEE. The estimated partitioning into GEE and ecosystem respiration (Resp), which are shown in the bottom panel, have both increased. The estimated partitioning suggests that a sharp increase in ecosystem respiration accounts for the 2009-2010 decline in NEE.

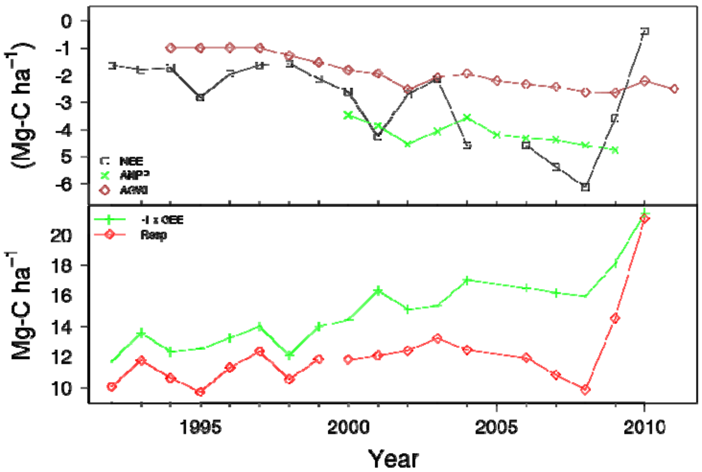

Figure 1 Annual sums of CO_2 Net ecosystem exchange (NEE), Ecosystem respiration (Resp), and Gross ecosystem exchange (GEE) observed at the HFEMS flux tower are shown for the years 1992 – 2010. NEE is partitioned into GEE and Resp using nighttime data to define temperature dependency of ecosystem respiration [*Urbanski et al.*, 2007]. In the upper panel NEE is compared to wood production and Above-ground Net Primary Production computed from woody increment and litter data**.**

The plot-based measurements show a large steady increase in red oak biomass dominating the overall biomass trend (Figure 2). The stock of dead carbon in coarse woody debris is fairly steady at 10% of the living, despite variability in mortality and inputs from severe storms. The biomass of hemlock, while not a large contributor overall has had a significant increase relative to its initial magnitude. The total biomass of all remaining species combined, which is mostly red maple with small contributions from birches, beech, pines, and other minor species has been relatively static. This pattern is consistent for this ecosystem with healthy growth by the mid-successional species that are dominating the canopy, and steady growth by the late successional species that are present as saplings and small below-canopy trees. The recruitment pattern, demonstrating that hemlock and beech dominate the growth in

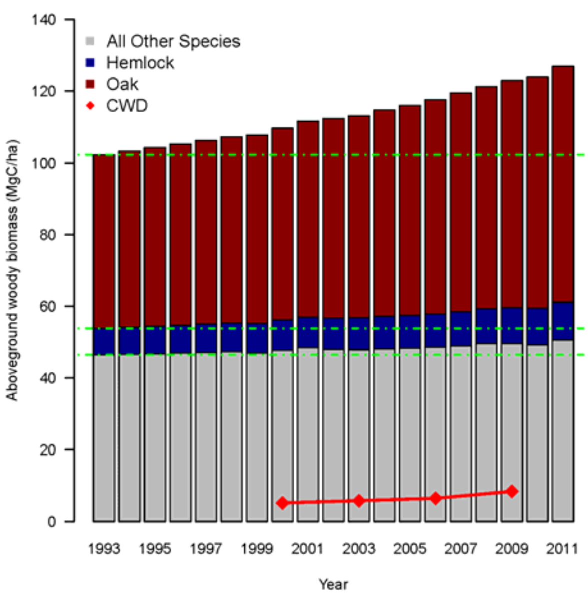

Figure 2 Time series of above ground woody biomass in trees > 10 cm dbh averaged across the EMS biometry plots. Biomass is computed from stem diameters and species-specific allometric equations. The grey bar indicates biomass for all species except red oak and hemlock, blue indicates the hemlock biomass and red is the oak. Green horizontal dashed lines illustrate the starting point for each class. Note that hemlock growth exceeds the growth of all other species combined, but is still less than the oak growth. The stock of CWD is shown by red line with diamond symbols

the smallest size cohort (10cm<dbh<15cm) is clearly shown in Figure 3. Most species are growing out of this size class and only the hemlock and beech are being replaced as the treess with dbh<10cm grow in. Understory surveys in 2004 and repeated in 2010 indicate there is significant biomass in this layer, and on average it contributes another 0.1 Mg-C $ha^{-1}y^{-1}$ to annual carbon storage (Figure 4).

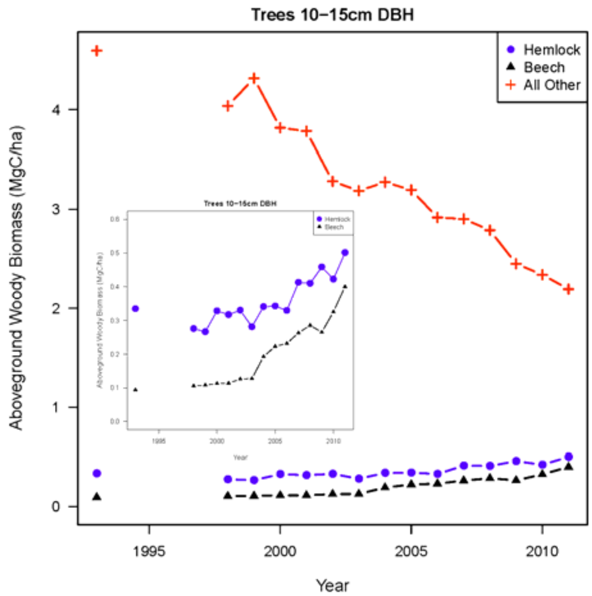

Figure 3 The biomass of trees between 10 and 15 cm dbh, which represent the cohort of subcanopy trees that will replace the dominant trees, is shown for beech, hemlock and all others. Beech and hemlock are shown separately in the inset. Note that beech and hemlock both have increasing biomass. The overall biomass of other species is declining as existing individuals grow into the next size class, but very few individuals are recruited from smaller sizes. The inset shows an expanded view of hemlock and beech increases.

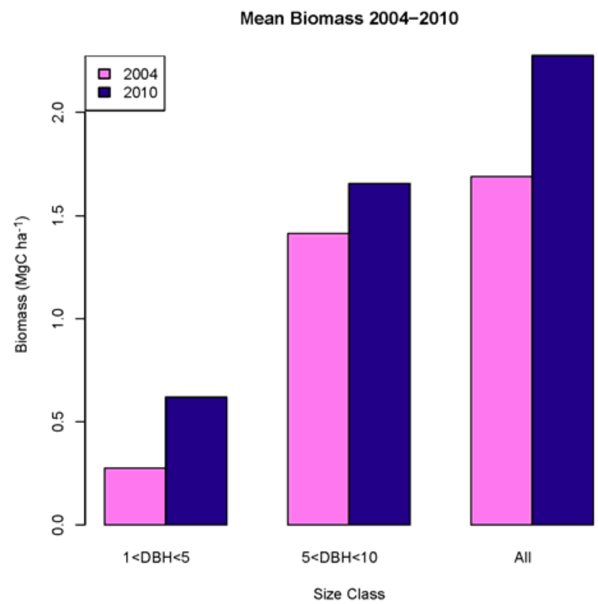

Figure 4 Understory biomass measured in 2004 and 2010 showing the distribution between <5cm and 5-10 cm stems and the net accumulation between the successive measurements.

Disturbance and Recovery

Disturbance events are an important control on interannual variability and multi-year trends. In the summer of 2009 we surveyed the EMS plots to quantify the impact of an ice storm that impacted Harvard Forest and surrounding region in December of 2008. The mean input of fine and coarse woody debris from the ice storm near the EMS tower was 0.46 and 0.57 Mg-C ha^{-1} (Figure 5), which was comparable to the cumulative input of woody debris from all other causes over the previous 3 years. The canopy damage, as quantified by FWD production, resulted in an average reduction of leaf area by 0.86 m^2m^{-2} (Figure 6) that only partially recovered by the summer of 2010. Two years later in the summer of 2011 the fine woody debris was resurveyed to assess its decomposition rate. Although some of the tagged

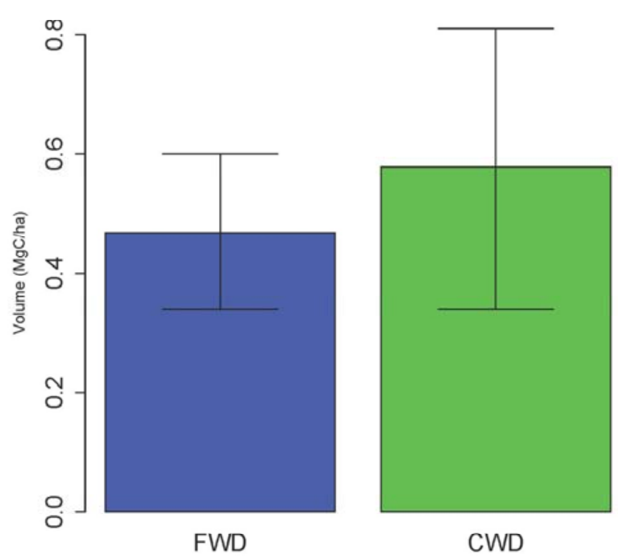

Figure 5 Mean mass of fine and coarse woody debris measured on the EMS biometry plots in the summer of 2009 following a winter 2008-2009 ice storm

pieces of debris were difficult to find, we determined that about half the mass of fine woody debris had been lost in 2 years (Figure 7). Changes in density, rather than volume were the

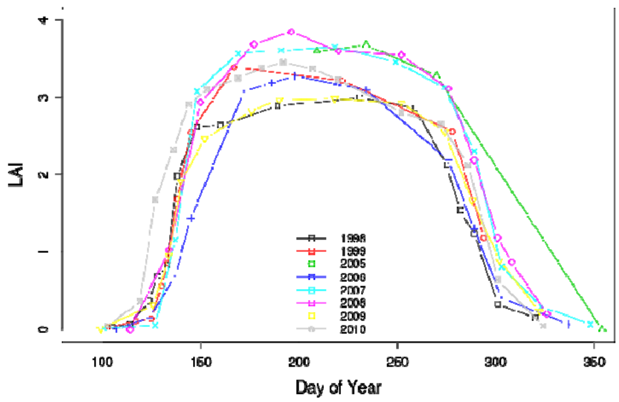

Figure 6 Mean values of deciduous leaf area index (LAI) observed over the EMS plots vs day of year for several years. LAI in 2009 is reduced relative to its 2008 value by ice-storm damage. LAI in 2010 is partially recovered, but still less than the pre storm value

Figure 7 Bars indicate the mass of carbon in fine woody debris generated by an ice storm in winter 2008-2009. First measurement was in the summer of 2009, when all the debris identified as being from the ice storm was tagged. The 2011 measurement resurveys the tagged debris. Error bars are the sampling standard deviations

primary mechanism. The additional carbon loss of 0.09 Mg C ha^{-1}y^{-1} contributes in part to the higher R_{eco} and reduced annual carbon uptake observed in 2009 and 2010.

Species composition is more important than stand age in explaining differences among the three

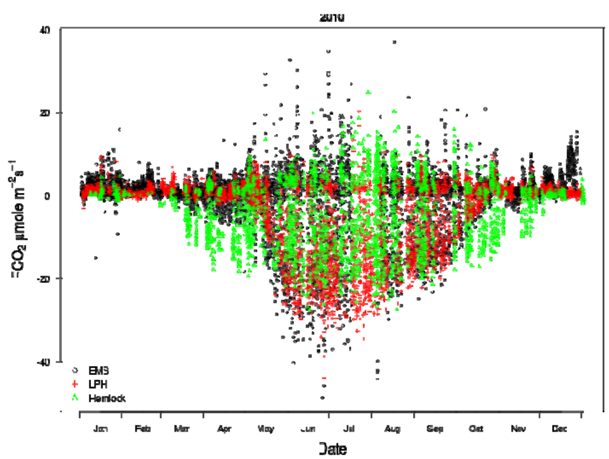

Figure 8 Observed rates of net CO_2 flux at the 3 Harvard Forest towers in 2010.

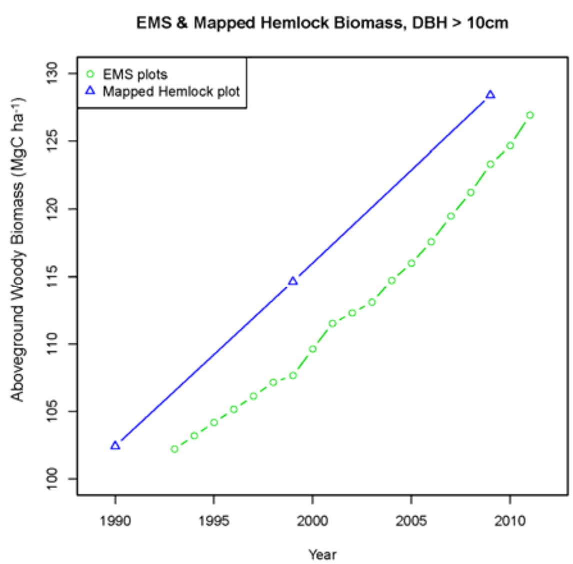

Figure 9 Above-ground woody biomass derived from diameter measurements on the array of EMS biometry plots and a mapped hemlock plot near the Hemlock tower. The EMS plots were established in 1993 and resurveyed annually after 1998. The Hemlock plot was established in 1990 and resampled about every 10 years.

tower sites. The EMS tower footprint is dominated by oak and maples established between 1900 and 1938, but also includes a significant fraction of hemlock in patches and as a sapling layer in the subcanopy. The LPH stand is dominated by oak and maple with many younger trees regenerating after a fire in 1957 and very few conifers. The Hemlock tower is dominated by a nearly pure stand of hemlock. Comparing the hourly CO_2 fluxes from the three towers highlights the similarities and differences in canopy physiology in the three stands (Figure 8). Hemlock has a much longer active season that starts in March and extends until November. The magnitudes of maximum CO_2 uptake in mid summer by older trees at EMS only slightly exceeds the peak uptake by a younger stand with similar species composition at LPH, but both have greater uptake than Hemlock. There is a distinct shoulder of modest uptake at EMS in the spring months, which we attribute to the presence of some conifers that are not present at LPH. Although the hemlock stand has a lower maximum photosynthetic rate, the longer growing season may compensate. Biomass accumulation in above-ground wood has been remarkably similar for hemlock and deciduous-dominated stands over the last decade (Figure 9). Even though the hemlock stands are older they are still actively accumulating carbon. Understanding the carbon budgets of hemlock stands is critical in light of the potential for region-wide decline as Hemlock Wooly Adelgid, an exotic insect pest that kills hemlock trees, continues to spread northward. Quantifying the impact on carbon, water, and energy balance as the infestation progresses is one focus of a pending proposal for continued study at Harvard Forest.

The data assimilation study presented in a manuscript submitted by Keenan et al (2012) highlights the importance of including data streams associated with processes occurring on both short and long time scales. The instantaneous rates of CO_2 uptake measured by the flux tower provide valuable insights into ecosystem response to climate drivers and variation in those functional dependencies over time, but are not sufficient by themselves to adequately constrain ecosystem models over annual to decadal intervals. Model uncertainty is most effectively reduced when flux data are combined with aggregated budgets in conjunction with a suite of ancillary biometric data. The data-constrained model clearly demonstrated that climate variability alone could not account for observed long-term trends in carbon uptake at Harvard Forest EMS stand. The upturn in carbon flux since 2000 could only be explained by allowing a substantial increase in canopy photosynthetic capacity (represented in the model by V_{Cmax}). Furthermore, the model results suggest that part of the increased carbon uptake was accumulating as slowly cycling soil organic matter. The model outcome should be viewed a testable hypothesis, which points to the need for better characterization of the composition and turnover time of carbon in forest floor organic matter. Organic matter in the forest floor is probably not as effective a long-term sink as the woody biomass, but it is a large reservoir with a sufficiently long residence time that can take many years to restore balance after a perturbation in the input or output of carbon from this pool.

Research products

Project data sets are posted to our in-house ftp servers as well as submitted to the AmeriFlux data server at Oak Ridge National Lab and made available as level 2-4 data files and biological data spreadsheets
http://public.ornl.gov/ameriflux/Site_Info/siteInfo.cfm?KEYID=us.harvard_forest.01
http://public.ornl.gov/ameriflux/Site_Info/siteInfo.cfm?KEYID=us.harvard_forest_hemlock.01
http://public.ornl.gov/ameriflux/Site_Info/siteInfo.cfm?KEYID=us.ma_little_prospect_hill.01

Data sets

1. Hourly fluxes of CO_2, H_2O, heat and momentum and estimated partitioning of NEE into the GEE and R_{eco} components, *available at;*
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/Final
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/Final/Filled
http://harvardforest.fas.harvard.edu/data/p10/hf103/hf103-03-flux-since-2004.csv
http://harvardforest.fas.harvard.edu/data/p07/hf072/hf072-02-eddy-2005-xxxx.csv

2. Annual above-ground woody biomass increment, litter input, and above-ground mortality and total stocks of live above-ground biomass in large trees (dbh > 10 cm) and coarse and fine woody debris *available at;*
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/ecological_data/trees/
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/ecological_data/woody_debris
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/ecological_data/litter
http://harvardforest.fas.harvard.edu/data/p15/hf151/hf151-01-hem-litterfall.csv
http://harvardforest.fas.harvard.edu/data/p15/hf151/hf151-02-lph-litterfall.csv
http://harvardforest.fas.harvard.edu/data/p14/hf149/hf149-01-hem-dendro.csv
http://harvardforest.fas.harvard.edu/data/p14/hf149/hf149-02-lph-dendro.csv

3. Time series of LAI and canopy nitrogen over the growing season *available at*;
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/ecological_data/lai
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/ecological_data/leaf.chemistry/
http://harvardforest.fas.harvard.edu/data/p15/hf150/hf150-01-hem-lai.csv
http://harvardforest.fas.harvard.edu/data/p15/hf150/hf150-02-lph-lai.csv

4. Surveys of understory vegetation near EMS tower *available at;*
ftp://ftp.as.harvard.edu/pub/nigec/HU_Wofsy/hf_data/ecological_data/trees/understory/

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