Final Technical Report
Interannual Variations in the Rate of Carbon Storage by a Mid-Latitude Forest
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Introduction

The time series of Net Ecosystem Exchange (NEE) of carbon by an entire forest ecosystem on time scales from hourly to decadal was measured by eddy-covariance supplemented with plot-level measurements of biomass and tree demography. The results demonstrate the response of forest carbon fluxes and long-term budgets to climatic factors and to successional change. The data from this project have been extensively used worldwide by the carbon cycle science community in support of model development and validation of remote sensing observations.

Harvard Forest Environmental Measurements Site

The flux tower at the Harvard Forest Environmental Measurements Site (HFEMS) was established in the fall of 1989 and began continuous measurements of CO_2 flux with consistent accuracy and quality in fall 1991. An array of biomass plots in the tower footprint was first measured in 1993 and has been re-measured annually since 1998. Harvard Forest is located in Petersham, Massachusetts, which is extensively forested and sparsely populated. The HFEMS is located within a 375 ha tract of research forest and is a component of the Harvard Forest Long-term Ecological Research (LTER) site, providing access to extensive ecological data archives and coordination with a variety of complementary ecological studies. The tower site is surrounded by mixed deciduous forest that is dominated by red oak and red maple with patches of eastern hemlock and scattered pines. Soil moisture is heterogeneous with fairly well drained conditions to the southwest of the tower and a small wetland and stream to the northwest.

Research Results

During the period 1995-2007 there have been three main phases to our research.

Phase 1; Method development and evaluation. At the outset of this work eddy covariance had been used in short field campaigns to observe ecosystem-scale responses to environmental drivers, but its application to defining seasonal and annual carbon budgets had not been shown. A key step in establishing the capability of long-term eddy covariance data for measuring NEE was to define the uncertainties associated with the method and its application at Harvard Forest. Using our extensive flux data and wide range of ancillary observations, we critically examined the uncertainty in terms of both accuracy and long-term (year-to-year) precision [*Goulden et al.,* 1996a].

We assessed both random and systematic errors. Effects of missing data were determined by Monte Carlo simulation of our gap-filling algorithm. We partitioned NEE into its component fluxes to help correct for systematic errors. We defined the respiration flux R at night by examining data from windy periods, after having determined that there is no apparent dependence of R on wind speed for $u^*>17$ cm s^{-1}. This work demonstrated the need to account for 'missing' nighttime fluxes during calm conditions when soil respiration continues to emit CO_2 but neither eddy flux nor profile measurements detect it. Failure to consider this creates a bias of 0.5 to 1 Mg C ha^{-1} in annual carbon fluxes [*Goulden et al.,* 1996a]. We developed corrections based on a u* threshold and extrapolation based on fitting valid nighttime data to temperature that have been the starting point for most flux data processing algorithms that are currently in use. Results from HFEMS have contributed to subsequent analyses of gap-filling strategies and uncertainty analysis [Falge et al., 2001a,b; Gu et al, 2005; Richardson et al., 2006, Yi et al, 2004]

Another contribution to method development was the work of *Bain et al*. [2005] that demonstrated the potential for artifacts in commonly used soil respiration chambers. Even very small pressure differences between the chamber and exterior induced mass flow through the porous soil and affected the apparent CO_2 efflux rate. Mismatches between the inflow and outflow in closed chamber systems and wind-induced pressure fluctuations around the chamber site could both be sources of pressure differences.

Phase 2: Merging flux and inventory data. Eddy-flux and biomass measurements provide a top-down and bottom-up approach to defining ecosystem carbon balance and address different temporal scales of variability. In a major paper published in 2001 [Barford et al., 2001], and a multi-site data synthesis in 2002 [Curtis, et al., 2002] we reconciled the Harvard Forest carbon budgets determined by integration of eddy flux data and from plot-based biomass measurements. Carbon budgets based on biometry data agree closely with the mean annual NEE, when averaged over the 9 years 1991-2000 (Table 1) (*Barford et al*. 2001). Above-ground woody increment (AGWI) dominated carbon uptake, accounting for 70% of the 8-yr mean ecosystem net uptake. Both growth and respiration depend on carbon fixed in previous years. Because the processes

Table 1. Carbon budget for Harvard Forest from biometry and NEE (mean of 1993-2000, Mg C ha^{-1} yr^{-1}). Numbers in parentheses give the 95% confidence intervals. Below ground fluxes were inferred as 20% of above ground values. CWD respiration was based on 6% mass loss per year from the estimated stock of CWD. Mortality uncertainty was not included in error propagation because net C storage due to mortality is zero (tree death transfers C from live to dead pools, giving equal and opposite contributions to AGWI and CWD). Change in soil carbon is based on the residence time of ^{14}C in Harvard Forest soils, measured by Gaudinski *et al*. (see Barford et al., 2001)

	Component	Totals
Δ Live biomass		
Above ground		
Growth (AGWI)	1.4 (±0.2)	
Mortality	- 0.6	
Below ground (inferred)	(±0.6)	
Growth		
Mortality	0.3	
Sub-total	- 0.1	1.0 (±0.2)
Δ Dead wood (CWD)		
Mortality		
Above ground	0.6 (±0.6)	
Below ground	0.1	
Respiration	-0.3 (±0.3)	
Sub-total		0.4 (±0.3)
Δ Soil (net) ‡		0.2 (±0.1)
Comparison of Budgets		
Σ Carbon budget		1.6 (±0.4)
Σ NEE (× -1)		1.9 (±0.4)

that take up and release CO_2 operate on different timescales it takes multiple years to reconcile NEE with biometry and accurately define the mean rates of C sequestration. Biomass measurements showed that red oaks contributed most to carbon uptake, while the other major tree, red maple, had nearly stable biomass.

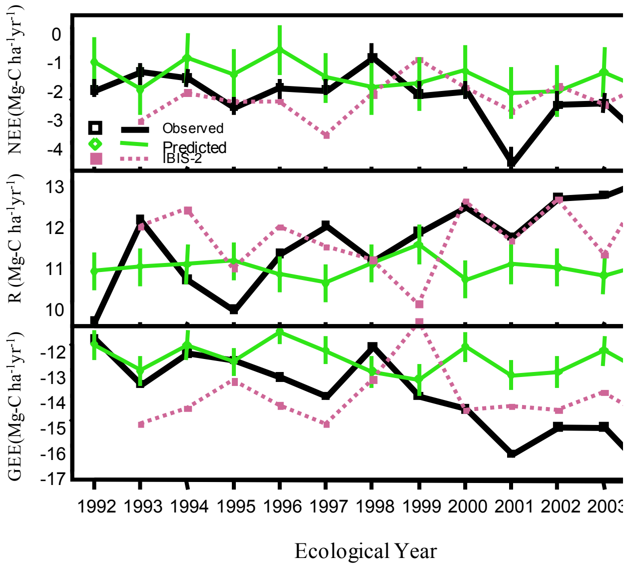

Figure 1 Annual sums of observed and predicted NEE, R and GEE at the Harvard Forest EMS. Annual sums are computed for 'Ecological' years, that are selected to start on the approximate date when photosynthesis ends in the fall (day 300) Heavy black line indicates the observed annual NEE, Solid green line indicates the annual sums predicted from mean temperature and light response functions. Vertical segments show the 90% confidence interval from a bootstrap calculation using the probablity distributions of the response parameters. Annual sums predicted from the IBIS-2 model are shown by the dashed red line (From Urbanski et al. [2007])

Phase 3: Analysis of interannual variability and trends. Urbanski et al. [2007] presented results analyzing interannual variability and trends in NEE at Harvard Forest. A simple statistical model that relates hourly NEE to temperature and light was used to define the mean ecosystem climate response (it is a "null" model with no driver of long term trends other than possible weather trends). The model accounts for up to 80% of variance in the observations during summer growing season, when large daily variation in light and temperature dominate the GEE and R patterns. However, variability in dormant season respiration is poorly predicted. However, when this statistical model is integrated to longer time scales it is unable to account for the observed patterns showing that long-term variability in forest carbon budgets is **NOT** directly dependent on climate variability (Figure 1).

Urbanski et al. [2007] noted the importance of disturbance events followed by slow recovery periods. Adverse weather conditions early in the 1998 growing season led to a reduction in canopy leaf area compared to previous years and to a depression in photosynthetic capacity that took several years to fully recover (Figure 2).

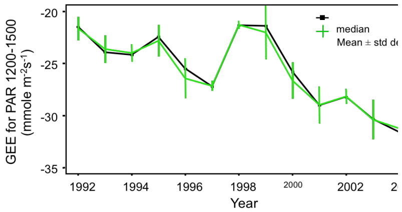

Figure 2 The mean and median of July GEE when PAR is between 1200 -1500 is shown for each year 1992-2004. Note the steady trend towards increased photosynthetic uptake, punctuated by an anomaly in 1998, and recovery over the following two years

HFEMS contributions to ecosystem modeling. The results from HFEMS have been used extensively in model evaluation and model development, as indicated by the many co-authored model papers listed in the Publications section. IBIS-2, a process-based ecosystem model was optimized using Harvard Forest data [*Kucharik et al*. 2006]. Although IBIS-2 accurately simulated the 12-year mean NEE of 2.3Mg-C $ha^{-1}y^{-1}$ that was observed at Harvard Forest from 1993 to 2004, it did not capture the interannual variability or long-term trend (see Figure 2) [Urbanski et al., 2007]. Furthermore, the reasonable agreement of annual means is due in part to offsetting biases in the modeled Respiration, which has an amplified seasonal cycle with too much respiration in summer and too little in winter compared to the observations.

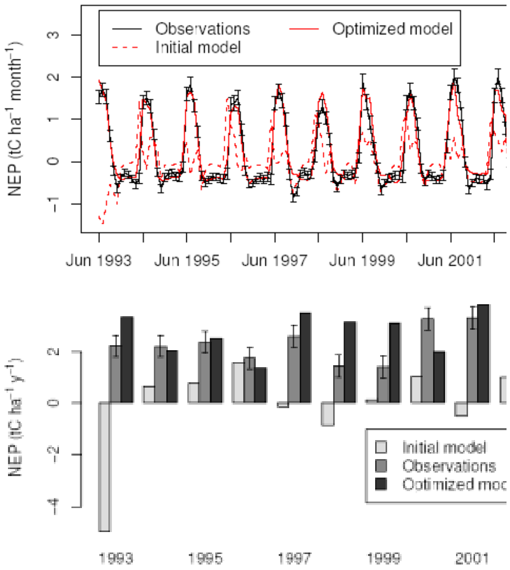

Figure 3 Predicted and observed patterns of Net Ecosystem Productivity (NEP) and rates of tree growth and mortality at Harvard Forest. (a) Black line shows the monthly patterns of NEP (Mg-C ha-1y-1) measured at the Harvard Flux Tower; dotted red line indicates the predictions of the initial (unoptimized) model; solid red line indicates the predictions of optimized model formulation. Error bars indicate the 2s error estimates for the observations.(b) Annual NEP in Mg-C ha-1y-1. The three bars for each year indicate, respectively, the predictions of the initial model (left), the flux-tower measurements (center), and the predictions of the optimized model (right). (adapted from Medvigy et al.. [2009].

The combination of high-frequency flux data with annual observations of biomass was ideal for constraining the Ecosystem Demography model (ED-2). *Medvigy et al. [2009]* report on results obtained by jointly optimizing the ED-2 model with hourly flux data for 1995-1996 and the observed forest inventory growth and mortality. After optimization the model simulation of annual NEE for the entire decade 1992-2001 was significantly improved (Figure 3). Surprisingly, the optimized parameters based on Harvard Forest data were able to accurately simulate NEE at Howland Forest, a conifer dominated site in northern Maine, by changing only the initial conditions to reflect the observed species composition. This demonstrates that plant functional types represented in the model behave similarly across a wide geographic range though their relative contributions to the overall carbon budgets are quite different at the two sites.

Summary of Harvard Forest Results

More than a decade of Net Ecosystem carbon exchange observations and ancillary ecological measurements at the Harvard Forest EMS tower have contributed significantly to improved understanding of terrestrial ecosystem processes that affect carbon storage. These results show that knowledge gained from short-term observations is not sufficient to understanding and predicting the long-term changes associated with climate response and ecosystem change. The results demonstrate how small shifts in ecosystem functioning that may be driven by changes in climate and vegetation dynamics operate over time to control interannual variations and long-term trends in NEE. The work at Harvard Forest helped pave the way for long-term flux observation networks including AmeriFlux and similar networks internationally

Publications based on work at the Harvard Forest EMS tower

(chronological order; 52 total 1995 – 2009)

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