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Factors Controlling Long- and Short-Term Sequestration of Atmospheric CO_2 in a Mid-latitude Forest

Carol C. Barford,[1]* Steven C. Wofsy,[1]† Michael L. Goulden,[2] J. William Munger,[1] Elizabeth Hammond Pyle,[1] Shawn P. Urbanski,[1] Lucy Hutyra,[1] Scott R. Saleska,[1] David Fitzjarrald,[3] Kathleen Moore[3]

Net uptake of carbon dioxide (CO_2) measured by eddy covariance in a 60- to 80-year-old forest averaged 2.0 ± 0.4 megagrams of carbon per hectare per year during 1993 to 2000, with interannual variations exceeding 50%. Biometry indicated storage of 1.6 ± 0.4 megagrams of carbon per hectare per year over 8 years, 60% in live biomass and the balance in coarse woody debris and soils, confirming eddy-covariance results. Weather and seasonal climate (e.g., variations in growing-season length or cloudiness) regulated seasonal and interannual fluctuations of carbon uptake. Legacies of prior disturbance and management, especially stand age and composition, controlled carbon uptake on the decadal time scale, implying that eastern forests could be managed for sequestration of carbon.

The terrestrial biosphere has sequestered significant amounts of atmospheric CO_2 since 1980, with major contributions from northern mid-latitude forests (*1–3*). The sink has varied interannually by a factor of 2 or more, correlating with global-scale climate variations (*4–6*), and may have increased in the 1990s (*3*). The magnitude of uptake attributed to mid-latitude forests is controversial, however, partly due to sharp disagreement between atmospheric inverse models and forest inventories (*7*). The cause of net C uptake is also uncertain, with recent studies variously citing land-use change (*8*, *9*), fire suppression (*10*), longer growing seasons (*11*), and fertilization by elevated CO_2 (*12*) or N deposition (*13*). These factors must be understood in order to predict growth rates of atmospheric CO_2 and to develop strategies for restraining future increases.

We report here rates of net ecosystem exchange (NEE) of CO_2 for 9 years in a northern hardwood forest (Harvard Forest, 42.5N, 72.2W) measured by using eddy-covariance techniques (*14–16*). These data are compared with 8 years of biometric measurements of species-specific changes in C storage in live and dead wood, showing where and how the forest is storing C. We determine the C budget and responses to environmental forcing, including diel variations, weather patterns (*14*), phenology, and interannual climate variability (*15*). Eddy fluxes may underreport respiration at night in calm winds (*17*), and methods for removing this bias (*18*) remain controversial. Here we address possible errors in eddy-covariance data using the biometric data and combine the observations to define the causes of C sequestration and its variation on time scales from hourly to decadal.

Eddy-covariance data extend from 28 October 1991 to 27 October 2000, with valid data for 46,500 of 79,000 hours. Gaps occurred for calibration, data transfer, intense precipitation, maintenance, equipment failure, and weak vertical exchange ($u^* < 20$ cm s^{-1}) (Fig. 1). Ecosystem respiration (R) was observed directly at night and extrapolated for daytime on the basis of day-night changes in soil temperature (*18*). Gross ecosystem exchange (GEE) was computed from (NEE − R). The 9-year mean annual NEE, −2.0 Mg C ha^{-1} $year^{-1}$, is similar to observations at other forested sites in the northeastern United States (*19*, *20*). Annual sums of NEE at this site are insensitive to u^* within the limits established for valid data (Fig. 1).

Biometric observations of tree growth and

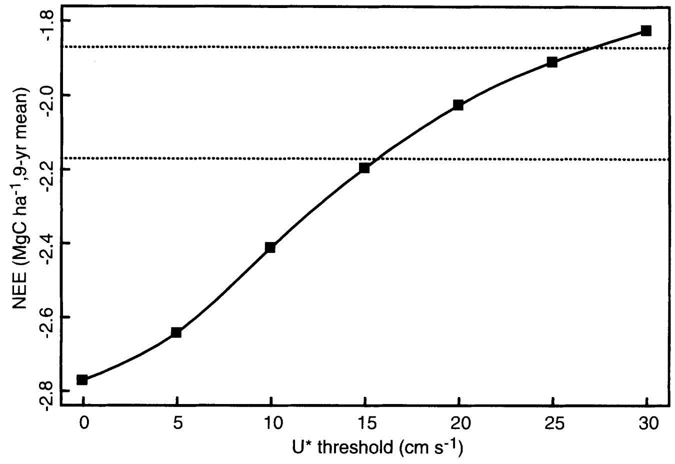

Fig. 1. Mean annual C uptake from eddy-covariance data versus the hourly-mean value, U^*, adopted for the minimum friction velocity u^* [≡ (−momentum flux)$^{1/2}$] threshold for valid data. Flux values for periods with $u^* < U^*$ are filled by interpolation (*18*). Dashed lines show the range of acceptable values for annual NEE (2.02 ± 0.15 Mg C ha^{-1} $year^{-1}$) on the basis of the criteria established in (*18*). Inclusion of flux data with $u^* < 17$ cm s^{-1} results in underestimation of R. Thresholds of $u^* > 30$ cm s^{-1} leave insufficient flux data for meaningful annual sums.

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[1] Division of Engineering and Applied Science and Department of Earth and Planetary Science, Harvard University, Cambridge, MA 02138, USA. [2] Department of Earth System Science, University of California, Irvine, CA 92697, USA. [3] Atmospheric Sciences Research Center, University at Albany, State University of New York, Albany, NY 12203, USA.

*Present address: Center for Sustainability and the Global Environment, Institute for Environmental Studies, University of Wisconsin, Madison, WI 53706, USA.

†To whom correspondence should be addressed. E-mail: steven_wofsy@harvard.edu

accumulation of coarse woody debris (CWD) were initiated in 1993 (*21–24*) to measure overall CO_2 sequestration and to provide more detailed information about C cycling at the site. Table 1 shows the mean C budget from biometric data. The average total rate of C sequestration, 1.6 ± 0.4 Mg C ha^{-1} year^{-1}, agrees well with the cumulative sum of eddy fluxes, providing independent confirmation of the C budget from eddy covariance at this site (Table 2 and Fig. 1).

Carbon sequestration on the decadal time scale was driven by historical land-use and disturbance, which determine critical characteristics of the ecosystem. Agriculture at the site was abandoned in the 19th century, and by the 1930s a stand of "old field" white pine was established. A hurricane in 1938 and subsequent salvage removed 70% of the crown area (*25*) and disturbed the soil, allowing establishment of a hardwood stand dominated by northern red oak (*Quercus rubra* L.). The present stand has 100 Mg C ha^{-1} above ground, which is ~80% of mean wood C in mature hardwood stands (*9*, *26*). Aboveground woody increment (AGWI) dominated C uptake during 1993 to 2000, accounting for 70% of 8-year mean ecosystem net uptake (biometric), a typical proportion for northern hardwoods (*27*). The rate of AGWI (mean rate of 1.4 Mg C ha^{-1} year^{-1}) (Table 1) varied little from year to year (Fig. 2) (*28*). Significant C also accumulated in CWD (Table 1), although less than in live trees, as expected for a maturing forest (*9*). NEE will likely decline as the stand matures, and the rate of net C storage in CWD should also diminish (*9*).

Tree growth rates are relatively slow at Harvard Forest (*29*), possibly due to N limitation in soils (*30*) resulting from pre–20th century N export in crops and fuel wood. Nitrogen limitation may also constrain the potential for CO_2 fertilization (*31*) at Harvard Forest. Deposition of anthropogenic N over past decades may have helped restore fertility, and thus contributed to C storage, but annual N deposition is modest, only ~12% of annual N mineralization (*32*).

Completely different processes govern NEE on shorter time scales, as shown by eddy-covariance data. Hourly and daily variations in NEE result from prompt ecosystem responses to ambient sunlight and temperature (*14*, *15*). Monthly and seasonal anomalies reflect primarily weather and climate variations (*15*). For example, low net uptake in 1998 (Table 2 and Fig. 2) was caused in part by reduced photosynthesis due to low temperatures and excess cloudiness in early summer (*33*). Net uptake was high in 1995 (*15*) because ecosystem respiration was depressed by dry surface soil in summer (*34*).

Seasonal climatic anomalies modify decomposition rates of fine organic matter, such as leaf litter, fine roots, and twigs. The resulting effects on NEE can emerge as variations on annual time scales, aliasing climatic variations. For example, winter anomalies in R (relative to 9-year monthly mean R) were positively correlated with R anomalies in the next growing season (Fig. 3, left panel), indicating that winter weather (e.g., snow cover) significantly influenced rates of decomposition over many months (*35*). Anomalies in winter NEE showed

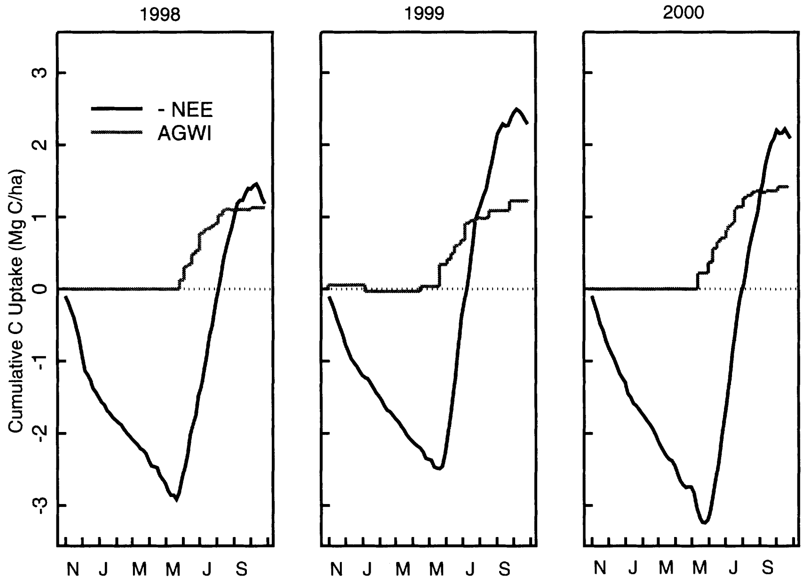

Fig. 2. Cumulative ecosystem net uptake (−1 × NEE) and AGWI for years with detailed dendrometry.

Table 1. Carbon budget for Harvard Forest from biometry, and NEE (mean of 1993 to 2000, Mg C ha^{-1} year^{-1}). Numbers in parentheses give the 95% confidence intervals. Belowground fluxes were inferred as 20% of aboveground values (*27*). CWD respiration was based on 6% mass loss per year (*40*) from the estimated stock of CWD (*39*). 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 C is based on the residence time of ^{14}C in Harvard Forest soils, measured by Gaudinski *et al.* (*44*).

	Component	Totals
Δ Live biomass		
A. Aboveground		
1. Growth (AGWI)	1.4 (± 0.2)	
2. Mortality	−0.6 (± 0.6)	
B. Belowground (estimated)		
1. Growth	0.3	
2. Mortality	−0.1	
Subtotal		1.0 (±0.2)
Δ Dead wood (CWD)		
A. Mortality		
1. Aboveground	0.6 (± 0.6)	
2. Belowground	0.1	
B. Respiration	−0.3 (± 0.3)*	
Subtotal		0.4 (±0.3)*
Δ Soil (net)		0.2 (±0.1)
Comparison of budgets		
Σ Carbon budget (NEP)		1.6 (± 0.4)
Σ NEE [× (−1)]		2.0 (±0.4)

*See (*39*).

Table 2. Annual CO_2 exchange (summed from 28 October of the previous year to 27 October of the nominal year). Negative values indicate CO_2 flux from the atmosphere to the ecosystem (i.e., storage).

Year	Annual exchange (Mg C ha^{-1} year^{-1})		
	NEE	GEE	R
1992	−2.0	−11.4	9.5
1993	−1.9	−13.3	11.4
1994	−2.0	−12.3	10.3
1995	−2.5	−12.3	9.9
1996	−2.0	−13.2	11.3
1997	−2.1	−13.9	11.8
1998	−1.2	−12.1	10.9
1999	−2.3	−13.9	11.6
2000	−2.1	−14.3	12.2
Mean	−2.0	−13.0	11.0

positive lagged correlations with early spring, when NEE $\sim$ R, but a negative association with NEE in late summer (Fig. 3, right panel). High rates of decomposition in winter appear to stimulate anomalously strong gross uptake in the following summer, possibly by increasing the availability of inorganic nutrients. Turnover times of leaf litter and other fine organic matter are a year or more, allowing seasonal climate anomalies to induce annual and interannual variations in C fluxes (*36*).

Growth rates, like respiration, depend partly on C fixed in previous years (*37*). Radial tree growth in deciduous trees begins by production of springwood in early May, up to 2 weeks before the daily average NEE becomes negative and before new leaves start to export carbohydrate (Fig. 2) (*37*, *38*). This springwood necessarily derives from stored carbohydrate and is affected by prior growing conditions.

Biometric C budgets should not be expected to reconcile with NEE in a single year due to annual shifts in C fluxes. For example, AGWI composed 100% of NEE in 1998 (Fig. 2), as compared with $\sim$70% for the long-term mean, indicating a transient budget imbalance given expected mortality, belowground growth, and so forth. Episodic tree mortality (0.4, 1.0, and 0.3 Mg C ha^{-1} year^{-1} aboveground in 1998 to 2000, respectively) (*39*, *40*) also contributed to annual budget imbalances. More observations are needed to reduce uncertainty in trends of mortality and CWD stocks. Reconciliation of a biometric budget with NEE in a single year is evidently subject to large errors, and several years are required to determine mean rates of C sequestration using either biometry or eddy covariance.

Short-term variations of NEE at Harvard Forest reflect prompt responses of the forest to environmental influences. Interannual variations reflect effects of weather and climate on ecosystem characteristics such as tree mortality, autotrophic and heterotrophic respiration, pool sizes of labile detritus, length of the growing season, and available light. Because seasonal and annual climatic anomalies are often coherent over large spatial scales (*5*, *6*), the processes described here are important in mediating observed interannual variations of the rate of increase of global atmospheric CO$_2$.

Rates of long-term C sequestration at Harvard Forest change much more slowly, because they are driven by ecosystem properties that evolve slowly, i.e., stand composition, biomass and mortality, soil fertility, and CWD pool size. The large areas occupied by mid-succession forests (30 to 100 years old) have been cited as the major factor in present terrestrial uptake of C (*41*, *42*). This work provides support for the view that historical legacies are a dominant factor in C sequestration for these lands. Unlike the environmental factors mediating interannual changes, the age structure, species composition, and health of forest ecosystems are subject to direct human intervention, indicating that long-term rates of C sequestration can be deliberately manipulated (*43*) through forest management.

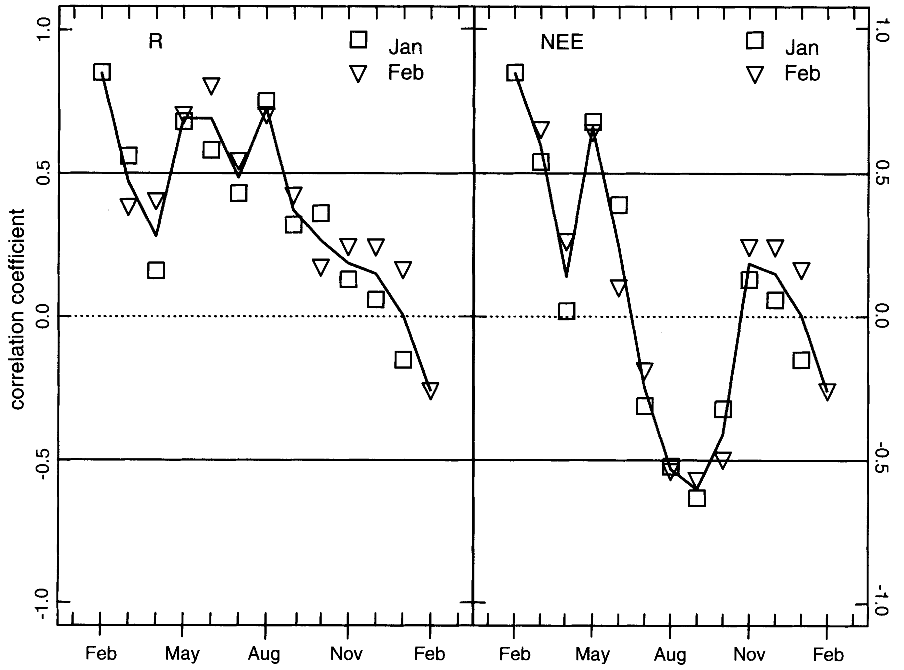

Fig. 3. Correlations of anomalies in NEE and R. Eddy-covariance data were block-averaged into monthly intervals, and anomalies were computed relative to the 9-year monthly averages. Coefficients (*r*) of correlations between the anomalies of R in winter (January and February) and anomalies of R in subsequent months (*x* axis) are shown in the left panel. Correlations between winter and subsequent anomalies in NEE are shown in the right panel. Note that during November through February, GEE $\approx$0, and thus NEE $\approx$ R. The set of correlation coefficients observed here is significant at the 95% confidence interval: assuming a null hypothesis in which anomalies at lags $<$ 3 months are autocorrelated, the probability of observing this pattern of correlations at lags $\geq$ 3 months with $|r| > 0.5$ is < 0.05 for both R and NEE (*33*).

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39. Annual variation in tree mortality did not contribute directly to uncertainty in the biometric C budget (see Table 1), but did add uncertainty to the estimate of the mean CWD respiration rate. To find this rate, we began with the current (year 2000) measured stock of aboveground CWD (7.5 Mg C ha^{-1}; composed of 5.5 Mg C ha^{-1} standing snags and 2.0 Mg C ha^{-1} logs). We then calculated the aboveground CWD present midway through the study, assuming constant tree mortality (mean mortality for 1993 to 2000 = 0.64 Mg C ha^{-1} year^{-1} aboveground). We assumed dead woody roots = 20% of aboveground CWD (*27*). We then calculated 6% annual loss of C (*40*) from the total time-averaged CWD pool. The confidence interval for CWD respiration (and thus for ΔCWD) reflects only the statistical uncertainty in the CWD pool size. There was no statistical basis for estimating the uncertainty associated with our choice of 6% annual respiration of CWD, and therefore we omitted it from the overall budget. Thus, it is possible that the confidence interval about the estimate of NEP should be slightly larger. However, we believe that the central estimate is conservative because the majority of standing snags in the CWD pool argues against rapid CWD decomposition.
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A Near-Earth Asteroid Population Estimate from the LINEAR Survey

Joseph Scott Stuart

I estimate the size and shape of the near-Earth asteroid (NEA) population using survey data from the Lincoln Near-Earth Asteroid Research (LINEAR) project, covering 375,000 square degrees of sky and including more than 1300 NEA detections. A simulation of detection probabilities for different values of orbital parameters and sizes combined with the detection statistics in a Bayesian framework provides a correction for observational bias and yields the NEA population distribution as a function of absolute magnitude, semi-major axis, eccentricity, and inclination. The NEA population is more highly inclined than previously estimated, and the total number of kilometer-sized NEAs is 1227^{+170}_{-90} (1σ).

Attempts to estimate the number of NEAs (*1*) have always been hampered by selection biases inherent to all observations as well as by small detection sample sizes. Bottke *et al.* (*2*, *3*) addressed this problem by using theoretical orbital dynamical constraints in combination with 138 detections from the SPACEWATCH program to constrain the size and shape of the NEA population. Rabinowitz *et al.* (*4*) estimated the NEA population using 45 detections from the NEAT program. Here, I use the order-of-magnitude larger detection sample size of the LINEAR project (*5*) to estimate the size and shape of the NEA population constrained solely by observational data. An estimate of the number of NEAs as a function of absolute magnitude, which is related to the size of the asteroid, is of critical importance in assessing the collision hazard for Earth. The distribution of the orbital parameters of the NEAs is important for understanding processes of solar system formation and dynamics and for evaluating the collision hazard.

In 3 years of operation, the LINEAR project searched almost 500,000 square degrees (*6*) of sky on nearly 600 nights, discovering 657 new NEAs and over 110,000 new main-belt asteroids. On many of the nights, however, the weather was sufficiently variable that it was difficult to characterize the limiting magnitude of the search. Selecting only the nights with stable atmospheric transparency leaves 412 nights, covers more than 375,000 square degrees of sky, and includes 1343 detections of 606 different near-Earth asteroids (Fig. 1).

To understand the selection biases of the LINEAR system, one must know where the telescope searched each night, the nightly brightness threshold for detecting an NEA, and the identities of all NEAs detected. The nightly observing logs provide the search locations and areas to within a few arcseconds. Determining the nightly brightness threshold is more difficult. Because of LINEAR's short integration times (*7*) and large pixels (2.2 by 2.2 arcseconds), NEAs move less than the size of a pixel. Asteroids and stars are all point sources, thus they can be treated with the same photometric model. The 50% detectability threshold is established using the signal-to-noise ratios of 200 to 300 cataloged solar-type stars in each field. The limiting magnitude for each night is then set by averaging these detectability thresholds. Uncertainty in the overall bias of the limiting magnitude calculation contributes to the error estimate in the derived number of NEAs. An estimate of this error is added in quadrature with the formal statistical errors described below to obtain the final error value for the number of NEAs and the error envelopes for the distributions.

To determine which NEAs were detected on any given night, the nightly telescope logs are combined with definitive identifications provided by the International Astronomical Union's Minor Planet Center (MPC). LINEAR reports all of its observations to the MPC, including those that have motions characteristic of main-belt asteroids, and provides intentional coverage overlap after a few nights or during the following month. This follow-up allows NEAs with motions initially mimicking main-belt asteroids to be identified, so that the number of detections not identified as NEAs is low, on the order of 1% of the number of NEA detections. Errors in which main-belt asteroids or false detections are erroneously labeled as NEAs are low because all NEA detections are verified on multiple nights, and usually by multiple observers, before orbits are issued by the MPC.

To determine correction factors for observational bias in the LINEAR search, I accounted for the time-correlated nature of the asteroid search space. I divided the orbital parameter space (a-e-i-H) into 49,200 bins (*8*). In each bin, I generated 144,000 asteroid orbits (*9*). Each of these 144,000 test particles is propagated through the time covered by the search and

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Massachusetts Institute of Technology Lincoln Laboratory, 244 Wood Street, Room S4-571, Lexington, MA 02421, USA. E-mail: stuart@ll.mit.edu