

Reassessment of Carbon Sequestration in Forests of Conterminous United States

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Summary:

The amounts and exact locations of atmospheric carbon (C) sequestered in forests vary greatly among estimates. An inverse modeling study¹, estimated that temperate North American forests sequester more C (1.7 Pg y^{-1}) than is emitted from fossil fuel consumption in North America ($>15^\circ\text{N}$), while none is sequestered in Eurasia forests. Coupling eddy covariance C exchange measurements and land cover data, we estimate the C sink in forests of conterminous United States (US_C) as only *ca.* 50% (0.78 Pg y^{-1}) of North American emissions. Owing to intensive management and long growing season, forests in southeast US_C appear as a dominant C sink, accounting for 50% the C sequestered North America. However, given the intensive forest management practiced in the southeast US, these forests may merely act as a strong C pump that affects seasonal biosphere-atmosphere C exchange, but contributes little to long-term C sequestration.

Introduction

The reversion of agricultural lands to forests in both Europe and the US, coupled with the fast growth of young forest stands, makes forests in the northern temperate belt effective sinks of atmospheric C³⁻⁶. Although inverse modeling estimated *NEE* for US_C at $350 \pm 100_{SD}$ g C m⁻² yr⁻¹, much lower values (*i.e.*, net ecosystem productivity *NEP* of 150 g C m⁻² yr⁻¹) have been estimated from biomass inventories⁷. Inverse modeling based on limited data are mass preserving, but may identify the distribution of C sinks imprecisely¹. In contrast, forest inventories can resolve the distribution at a subcontinental scale⁷, but such inventories cannot account accurately for the change in the entire C pool. Hence, both of these methods have difficulties in resolving the relative amount and location of the maximum C sink.

Objective:

Here we provide an independent estimate of the C sink in US_C using new eddy covariance C flux measurements⁸ from a site in the fast growing southeast US forest, and published estimates from other sites (Table 1), in combination with forest cover data.

We estimated the magnitude of *NEE* above a 15-year-old loblolly pine forest, a major component of the southeastern forest⁹, from August 1997 through February 1999. We also assessed the effect of drought on *NEE* using soil moisture, transpiration, and eddy covariance water vapour flux measurements given that General Circulation Models project intensified droughts in the Southeast.

Table 1. Annual or growing season (when in []) net ecosystem C exchange (*NEE*) for several forest types in two biomes.

<i>Biome</i>	Longitude	Age	<i>NEE</i>	Reference
Forest type		(y)	(g C m ⁻² y ⁻¹)	
<i>Boreal</i>				
black spruce ¹	54.0°N	115	[95] (±21)	25
Jack pine ²	53.7°N	75-90	[47]	26
aspen ³	53.7°N	75	200, 130 (±21)	27
<i>Temperate</i>				
oak/pine ⁴	42.5°N	50-70	Mean: 212 (±40) 280, 220, 140, 210, 210	28
oak/pine ⁵	36.0°N	50	525 (105)	13
loblolly pine ⁶	35.9°N	15	723 (±145*), 826 [†]	this study
slash pine ⁷	29.7°N	24	740, 610	14
cypress swamp ⁸	29.7°N	<130	84, 37	14

Codes next to forest types correspond to areas identified in Fig. 2, which were used to extrapolate to regional *NEE* (Table 2). In *NEE*, ± represents estimated error, except for * true spatial variance based on flux measurements at seven towers¹⁹; estimated for a year without drought (see text).

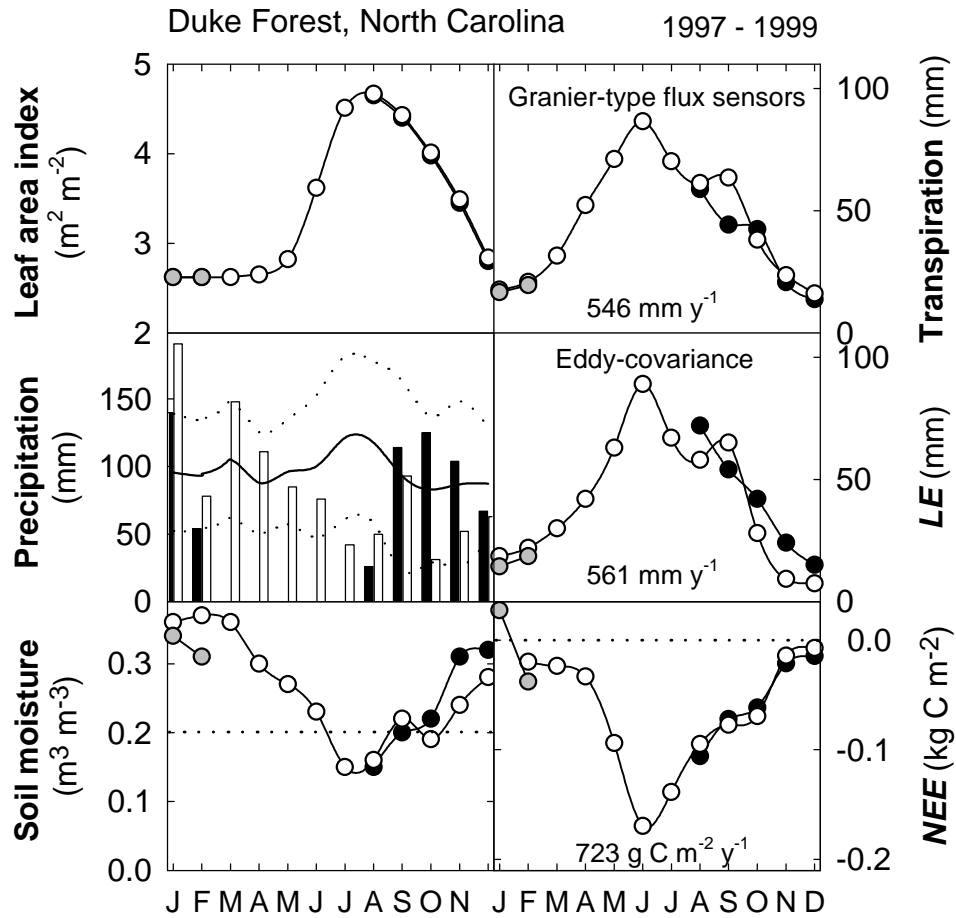


Fig. 1. Monthly means of site and environmental variables (*left*) and of fluxes (*LE* is latent heat flux measured using eddy covariance technique) during 17 months at a loblolly pine forest. Data from 1997 are in *filled symbols*, from 1998 in *open symbols*, and from 1999 in *shaded symbols*. For precipitation, the *solid line* is the 40-year average monthly precipitation, and the *dotted lines* are ± 1 SD. When soil moisture is below the *dotted line* stomatal conductance is reduced¹⁶. Negative *NEE* indicates uptake of CO_2 .

Extrapolating Flux Measurements to the US_c

To extrapolate the *NEE* estimates at individual sites (Table 1) to the C sink in US_C, the US_C was divided into five regions using information on vegetation and climate that reflect forest types and Ecosystem Divisions. We reclassified 21 forest types to 11 based on weather and species similarities (Fig. 2; Table 2) to reflect the relatively sparse availability of published flux data (see Table 1).

Estimate of the land area covered by forests within each region at 1-km resolution was based on forest types data²³, and on classified ecosystem provinces and divisions²⁴. Climate parameters used for combining forest types were the length of growing season, mean annual and/or mean seasonal temperatures, and precipitation amount and seasonal distribution. The five regions combine relatively similar ecosystem divisions.

Matching forest type (Fig. 2) with flux sites (Table 1), our extrapolated C sink estimate for the US_C is 0.78 Pg y⁻¹, near the lower bound of the most recent inverse modeling estimate¹.

On the other hand, the calculated area-weighted average of net C exchange ($\langle NEE \rangle$) of 307 g C m⁻² y⁻¹ in the forested area (Table 2) is twice the estimate using biomass inventory⁷.

Our simple extrapolation also shows that, although the forest cover in southeast US represents 27% of the total in US_C, the regional *NEE* estimate for the southeast is nearly half the *NEE* in US_C.

Table 2. Total land area, forest area, and mean annual *NEE* weighted by the respective forest area ($\langle NEE \rangle$)* for each region in Fig. 2, summed for the conterminous US (US_C).

	<i>SE</i>	<i>NE</i>	<i>Central</i>	<i>NW</i>	<i>SW</i>	US _C
Total area Km ² · 10 ³	1312.9	2217.4	3644.1	273.9	328.9	7777
						.2
Forest area Km ² · 10 ³	681.6	897.1	575.0	205.7	180.7	2540
						.0
$\langle NEE \rangle$ g C m ⁻² y ⁻¹	551	278	152 [†]	199 [†]	130 [†]	307
<i>NEE</i> Pg C y ⁻¹ (%)	0.38 (49)	0.25 (32)	0.09 (12)	0.04 (5)	0.02 (3)	0.78
Effects of annual variability						
Using weighted mean $\langle NEE \rangle + 50$ g C m ⁻² y ⁻¹						
<i>NEE</i> Pg C y ⁻¹ (%)	0.41 (46)	0.29 (32)	0.12 (13)	0.05 (6)	0.03 (3)	0.90
Using weighted mean $\langle NEE \rangle - 50$ g C m ⁻² y ⁻¹						
<i>NEE</i> Pg C y ⁻¹ (%)	0.34 (53)	0.20 (31)	0.06 (9)	0.03 (5)	0.01 (2)	0.64

Regional *NEE* is the product of $\langle NEE \rangle$ and the forest area. The potential effects of annual variation in $\langle NEE \rangle$ on regional *NEE* was evaluated by adding or subtracting 50 g m⁻² y⁻¹ (see text), and recalculating regional *NEE*. *Where more than one value is provided in Table 1, the mean is used; where two codes are shown, the mean is used, except in Eastern hardwood where only site 5 is used for the *SE* and *Central* regions; where *NEE* is available for the growing season only, the value is reduced to 0.75 reflecting non-growing season ecosystem respiration. [†]Because annual *NEE* estimates have not been published for western US, based on biomass inventory⁷ annual *NEE* was assumed = 200 g C m⁻² for western conifers and hardwoods (Fig. 2), and 100 g C m⁻² for pinyon-juniper and chaparral. Forest area within each region and forest type is available upon request.

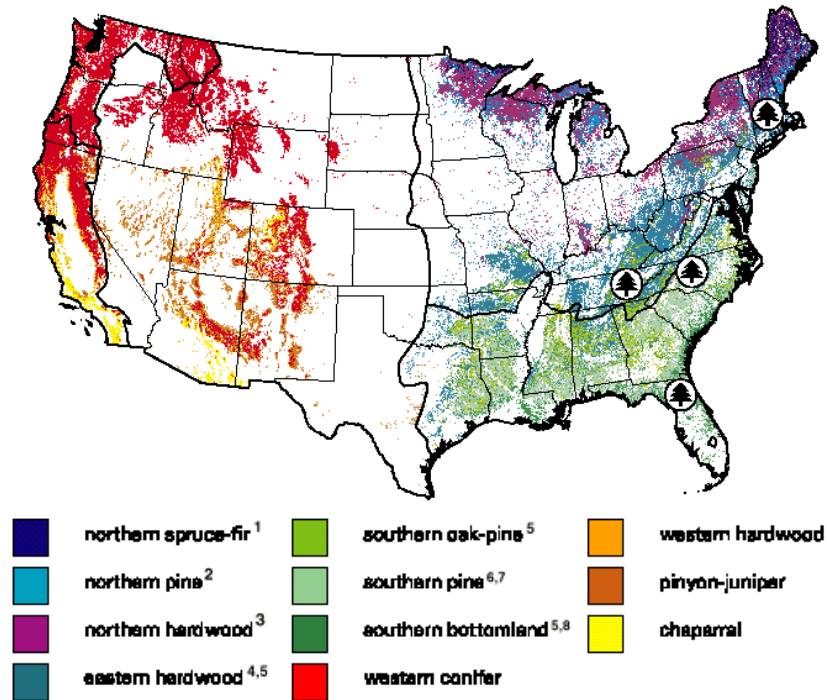


Fig. 2. Forested area in the conterminous US partitioned into five regions based on climate parameters and the prevailing forest types (see text). The codes identify flux sites (Table 1) used in conjunction with area covered by each forest type to calculate net ecosystem carbon exchange (Table 2).

Variability of NEE at Duke Forest:

Inter-annual variability in climate results in large annual variation in NEE^{11-14} even at one site (*e.g.*, two-fold difference at Harvard Forest¹¹). Given the dominant contribution of the southeast US forest to the C sink in the US_C , it is important to quantify the inter-annual variation in the NEE of this forest.

Pine stands over large areas in southeast US sites suffer periodic droughts⁹, and drought frequency and severity during the growing season have increased in the southeast, and may continue to increase with changing climate¹⁵. Monthly mean soil moisture (q) in the rooting zone was below that which limits stomatal conductance¹⁶ (*i.e.*, $q < 0.2 \text{ m}^3 \text{ m}^{-3}$) during two months in each growing season (Fig. 1).

The ratio of canopy net photosynthesis A_{net} to transpiration in the ecosystem (the slope in Fig. 3A) was unaffected by q .

However, in the months with $q < 0.2 \text{ m}^3 \text{ m}^{-3}$ (Fig. 1), transpiration is clearly reduced (Fig. 3B). This reduction was estimated (using the relationship in Fig. 3B, and leaf area index) as 75 mm y^{-1} . Based on Fig. 3A, the reduction in transpiration amounts to a reduction in annual A_{net} of 171 g C m^{-2} .

Thus, given that NEE is 60% of A_{net} , the drought-caused reduction in annual NEE is 103 g C m^{-2} in this stand, remarkably similar to observed variability in annual NEE reported at other sites (Table 1).

Consequently, in relative terms NEE in the southeast US should vary less than that in other regions, and thus should contribute a large proportion of NEE in North America regardless of how climate varies.

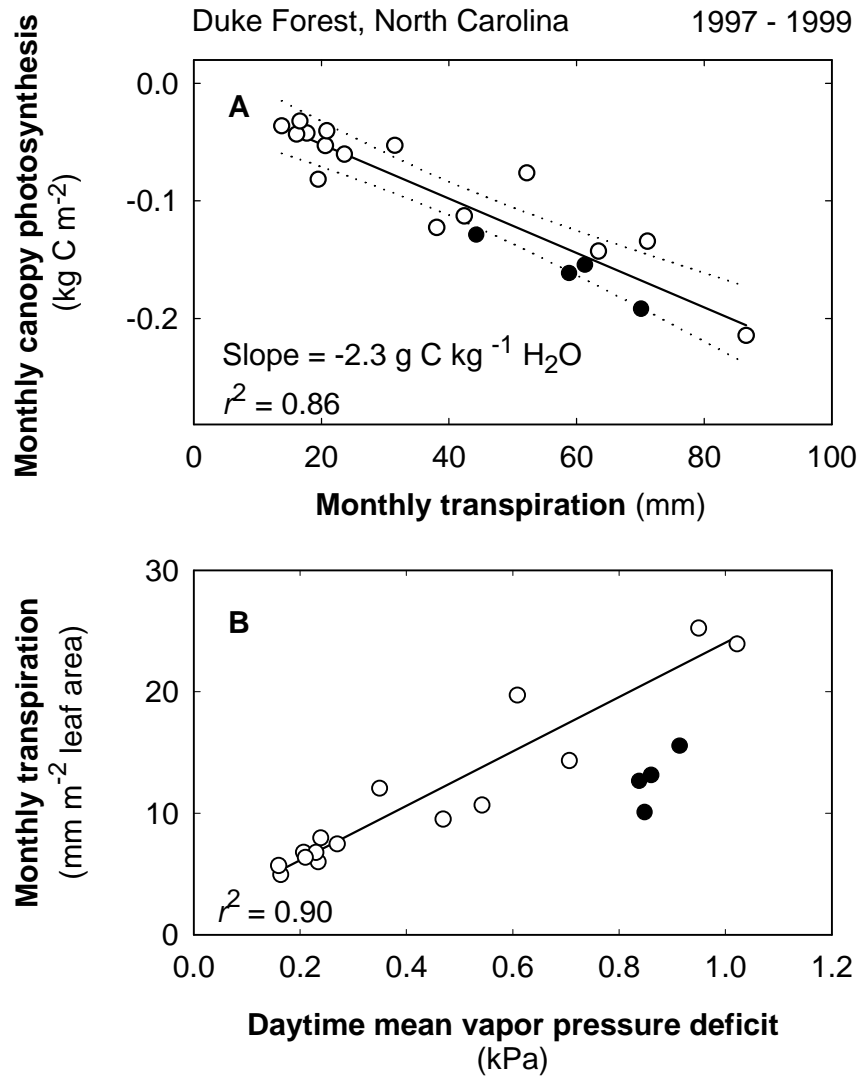


Fig. 3. (A) Variation in monthly transpiration was correlated with monthly A_{net} with no distinction between months in which soil moisture was either greater (*open symbols*) or less than $<0.2 \text{ m}^{-3} \text{ m}^{-3}$ (*filled symbols*). (B) Variation in monthly mean transpiration was highly correlated to the daytime mean atmospheric vapour pressure deficit when soil moisture was not limiting, but was reduced below expected values at low soil moisture (*symbols* as in A). To account for seasonality, transpiration was normalized by leaf area index and vapour pressure deficit by daylength. Negative A_{net} indicates uptake of CO_2 .

Sensitivity Analysis

By considering the maximum difference in annual *NEE* (averaging 98 [39_{SD}] g C m⁻² y⁻¹) at sites with multiple estimates (Table 1), and using a synchronous perturbation of ± 50 g C m⁻² y⁻¹ in *NEE*, the estimated C sequestration in US_C ranges from 56% to 40% of emissions (0.90 to 0.64 Pg C y⁻¹; Table 2).

The contribution of the southeast to the US_C C sink increases from 46% to 53% as conditions for photosynthesis worsen in all regions (Table 2). Southeast US forests remain a dominant C sink (41%) even for an asynchronous perturbation with adverse conditions (*i.e.*, resulting in 50 g C m⁻² y⁻¹ less than the mean) in the southeast and favorable conditions elsewhere.

Thus, the forests of the southeast US appear to absorb a quarter or more of C emitted in North America.

Sampling Biases:

Large spatial variation in *NEE* are expected even within one forest type at different locations¹³ (*e.g.*, compare the two oak/pine stands in Table 2). The developmental stage of forests has a large effect on *NEE* because, as forests age, a larger proportion of A_{net} is consumed by ecosystem respiration¹⁷.

Thus, a sampling regime that emphasizes younger forests (*e.g.*, in the southeast, Table 2) will systematically bias upward estimates of average *NEE*. For these reasons, caution must be used in interpreting absolute values from such a simple scaling scheme¹⁸.

Additional Evidence that the Dominant C Sink Location is the Southeast.

Nevertheless, additional lines of evidence in support of southeast US forests as the dominant C sink in North America can be found in that in southeast US forests (i) environment and species combine to result in high productivity⁹, and (ii) management practices maintain large forest areas at the most productive stage of development^{7,9}.

However, the intensive management of southeast US forests⁷ is accompanied by intensive harvest. This means that their contribution to C sequestration can only be evaluated if the fate of forest products is known.

It is conceivable that if the life span of these products is short, forests in the southeast US may act more like a C pump than a C sink, and in the limit this has the important consequence that C sequestration in North America decreases to only a quarter of emissions.

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Acknowledgments: We thank Dean Urban and Pat Halpin for assistance in using GIS software. The study was supported by: U.S. Department of Energy's National Institute for Global Environmental Change (NIGEC) through its Southeast Regional Center at the University of Alabama, Tuscaloosa. (DOE Cooperative Agreement DE-FC03-90ER61010), the U.S. Dept. of Energy, Office of Health and Environmental Research, U.S. Department of Energy contract DE-AC02-98CH10886 at Brookhaven National Laboratory, and the National Science Foundation (NSF-BIR 12333). Correspondence and requests for materials should be addressed to Ram Oren (e-mail: ramoren@duke.edu).