EOS
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 87 NUMBER 8
21 FEBRUARY 2006
PAGES 85–96

Estimating Carbon Budgets for U.S. Ecosystems

PAGES 85, 90

On a global basis, plants and soils may hold more than twice the amount of carbon present in the atmosphere [*Geider et al.,* 2001]. Under increasing atmospheric carbon dioxide (CO_2) concentrations and subsequently warming temperatures, these large biogenic pools may change in size [*Cox et al.,* 2000]. Due to a lack of long-term field studies, there is uncertainty as to whether vegetation and soils will act as a net sink or a source of atmospheric CO_2 in coming years. It is certain, however, that no retrospective analysis of the U.S. carbon balance will be possible without a comprehensive historical baseline of the sizes of various ecosystem carbon pools and the variability in their net annual increments.

This article provides one of the first spatially detailed terrestrial carbon budgets for the regions of the continental United States in the 1980s and 1990s. At a resolution of less than 10 kilometers, this carbon accounting estimation includes major vegetation and surface soil pools and is based on remote sensing and vegetation-soil modeling for ecosystems.

Results of this estimation imply that the past sink potential for CO_2 sequestration in U.S. ecosystems has been small and variable, but that the amounts of carbon stored in surface soils and woody litter pools comprise the largest sink. Because surface soils and woody litter pools respire CO_2 at higher rates when disturbed or when temperatures rise, this carbon sink is vulnerable to losses by wildfire, land use conversions, and climate change.

Remote Sensing and Modeling Methods

To estimate the current amount of carbon stored in Earth's terrestrial ecosystems, the NASA Carnegie-Ames-Stanford (NASA-CASA) model [*Potter et al.,* 2003] was used to generate continental maps of net primary production (NPP) from rates of both atmospheric carbon uptake and potential biomass accumulation. Because NPP and biomass accumulation rates vary as seasons change, monthly NPP flux of atmospheric CO_2 was predicted using vegetation reflectance properties from the Advanced Very High Resolution Radiometer (AVHRR) satellite, which maps the density of living vegetation cover over the globe according to the Normalized Difference Vegetation Index (NDVI). NDVI yields high values for lush vegetation based, in part, on strong near-infrared reflectance off green plants. Potential NPP rates, based on NDVI images, were then attenuated by time-varying observations of surface solar irradiance from ground stations. The NPP rates were also attenuated by model-predicted stress terms that gauged temperature and moisture effects on the estimated value of the maximum possible light utilization efficiency by land plants ($e_{\max}$).

Mean monthly climate (surface temperature, precipitation, and solar radiation flux) from previous modeling experiments [*Kittel et al.,* 2000] was used as historical (pre-1980s) climate inputs into the CASA model at 8-kilometer spatial resolution. Following a 300-year initialization sequence for soil carbon pools using long-term inputs, monthly precipitation and temperature data from DAYMET, a model that calculates daily values of temperature, precipitation, humidity, and radiation over complex land cover [*Thorton et al.,* 1997], were used as model drivers from 1982 to 1997. The Moderate-Resolution Imaging Spectroradiometer (MODIS) one-kilometer land cover map [*Friedl et al.,* 2002] specified predominant land cover classes.

Estimation of the global $e_{\max}$ value has been evaluated by comparing predicted annual NPP from the CASA model to more than 1900 field-based measurements spanning a wide variety of land cover across the globe made by many ecologists and forest scientists [*Potter et al.,* 2003]. Based on this cross-check procedure, error terms of ±10% are reported for regional-scale NPP predictions. The CASA model estimates for NPP have been validated against field-based measurements of crop production, forest ecosystem fluxes, and inventory estimates of carbon pool sizes at multiple locations in North America [*Hicke et al.,* 2002].

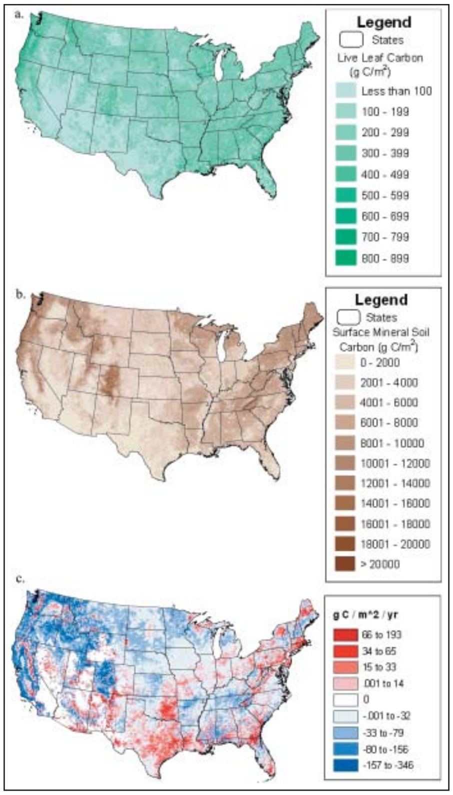

Fig. 1. Nationwide baseline estimates from the NASA-CASA model for (a) live leaf carbon and (b) surface soil carbon pools, both circa late 1990s. In the NASA-CASA model, predicted surface soil amounts do not include soil carbon stored in layers deeper than 30 centimeters, which could be considerably larger. (c) Net ecosystem production (NEP) estimated as the sum of carbon fluxes for 1982–1997. Net gains of carbon from the atmosphere are shown as positive NEP values, whereas net losses of carbon from ecosystems to the atmosphere are shown as negative NEP values, both on a unit area basis. Original color image appears at the back of this volume.

The NASA-CASA model couples seasonal patterns of NPP to soil heterotrophic respiration (Rh) of CO_2 from soils. Biomass pools estimated from the worldwide remote sensing data are simulated to die, decay, and respire in a coupled modeling scheme for soils. First-order decay equations simulate exchanges of decomposing plant residue (metabolic and structural fractions of litter) at the soil surface. The model simulates surface soil organic matter (SOM) fractions that presumably vary in age and chemical com-

---

By C. Potter, S. Klooster, R. Nemani, V. Genovese, S. Hiatt, M. Fladeland, and P. Gross

Table 1. Estimates From the NASA-CASA Model for Baseline Carbon Pools (Circa 1997) and Annual NPP Fluxes in Regions of the Continental United States[a]

	U.S. Region[b]	*Land Area, 10^3 km^2*	*NPP (1997), Pg C yr^{1}*	*Nonforest Leaf Biomass, Pg C*	*Nonforest Wood Biomass, Pg C*	*WoodyLitter, Pg C*	*Surface Soil, Pg C*	*Total Pools, Pg C*
1	New England	193.9	0.12	0.002	0.001	0.41	1.53	1.93
2	Northeast	158.3	0.09	0.012	0.006	0.28	0.96	1.26
3	Mid-Atlantic	321.7	0.21	0.019	0.003	0.52	1.90	2.44
4	Southeast	1002.0	0.66	0.138	0.067	1.17	3.97	5.28
5	North central	885.6	0.47	0.158	0.002	0.89	3.50	4.55
6	South central	1487.9	0.61	0.276	1.618	1.21	3.28	4.76
7	Midwest	737.0	0.34	0.182	0.074	0.33	1.97	2.48
8	Rocky Mountain	1453.4	0.43	0.256	1.376	0.93	5.24	6.43
9	Pacific southwest	1009.6	0.21	0.053	2.768	0.73	2.36	3.15
10	Pacific Northwest	641.0	0.28	0.068	0.680	0.97	3.89	4.93
	Total	7890.5	3.42	1.164	6.593	7.44	28.60	37.21

[a] Nonforest ecosystems include grasslands, croplands, shrublands, and savannas. Standing wood biomass estimates from the CASA model for U.S. forest ecosystems are not included in this table; 1 Pg = 1 petagram, or 1 billion metric tons.

[b] U.S. Environmental Protection Agency regions: 1, Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont; 2, New Jersey, New York; 3, Delaware, Maryland, Pennsylvania, Virginia, West Virginia, District of Columbia; 4, Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee; 5, Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin; 6, Arkansas, Louisiana, New Mexico, Oklahoma, Texas; 7, Iowa, Kansas, Missouri, Nebraska; 8, Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming; 9, Arizona, California, Nevada; 10, Idaho, Oregon, Washington.

position. The model's interannual estimates for net ecosystem exchange of carbon, which includes soil CO_2 flux predictions, has been validated at both local and global scales [*Potter et al.*, 2003].

Carbon Model Results

The NASA-CASA model predicts carbon storage in the baseline pools of major ecosystem 'strata': live leaf, standing wood of trees and shrubs, dead woody litter, and surface soil carbon. The estimated distribution of carbon in live leaf pools (Figure 1a) showed the highest biomass storage density in forests of the Pacific Northwest, Rocky Mountain, and southeast regions. Carbon pools in nonforest biomass (grasslands, croplands, and shrublands classes from MODIS land cover) were highest in the south central, Rocky Mountain, and Pacific southwest regions (Table 1). These nonforest ecosystems represent a baseline of about 7.8 petagrams of carbon in live leaf and wood pools combined.

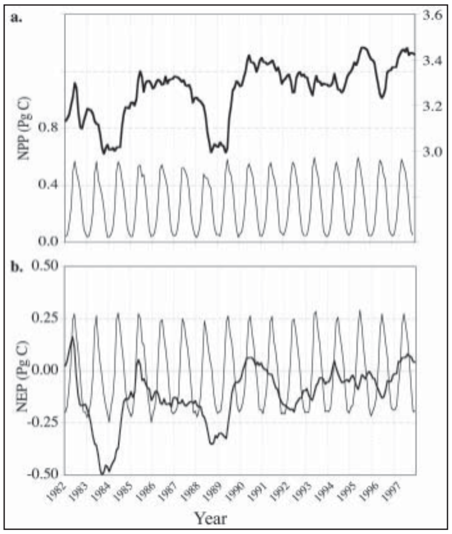

Fig. 2. Estimated time series of (a) NPP and (b) net ecosystem production (NEP) from the NASA-CASA model over 1982–1997. Monthly model predictions are shown (thin curves) with their 12-month running average (bold curves).

Carbon stored in dead wood pools nationwide (forests and shrublands combined) was estimated from the NASA-CASA model at 7.4 petagrams of carbon. The geographic distribution of this decomposing woody pool appears to be fairly evenly spread across the southeast, south central, Rocky Mountain, and Pacific regions of the country (Table 1).

Surface soil pools represent the largest baseline pool of carbon in the continental United States, estimated at 28.6 petagrams of carbon nationwide (Figure 1b). This is a complex pool of decomposing carbon stored in surface organic and mineral soil layers to a depth of approximately 30 centimeters, with a mean residence time less than 25 years. Northern forest and mountainous areas of the country store the largest pools of surface soil carbon. The Rocky Mountain, north central, southeast, south central, and Pacific Northwest regions store more than three petagrams each of carbon in surface mineral pools (Table 1).

Predicted NPP fluxes from the NASA-CASA model over the period from 1982–1997 indicate interannual variability nationwide at the level of 3–3.5 petagrams of carbon per year (Figure 2). The southeast and south central regions of the country typically contributed >35% of the nation's total annual NPP. The years of lowest annual NPP were 1983 and 1988, during which the growing seasons were affected by extensive droughts [*Potter et al.*, 2005].

Although net primary production was estimated to increase on a nationwide basis during the 1990s to nearly 3.5 petagrams of carbon per year, CASA results suggest that net terrestrial CO_2 sink in U.S. ecosystems never exceeded 0.05 petagrams of carbon per year in the positive direction. During the drought years of 1983 and 1988, the continental United States was predicted to have lost 0.46 and 0.32 petagrams of carbon, respectively, in net ecosystem production (NEP = NPP - Rh). Over 1982–1997, the total predicted NEP flux from continental U.S. ecosystems was 1.85 petagrams of carbon lost to the atmosphere. The Pacific and Rocky Mountain regions of the country were estimated to have had the largest net losses of the carbon from ecosystems, while New England, the northeast, and the southern regions of the country were estimated to have had the largest net gains of the carbon in ecosystems on a unit area basis (Figure 1c). Changes in seasonal NPP resulting from periodic droughts and temperature variations are likely the main controls on predicted NEP fluxes for any given year.

Implications for Conservation Efforts

A baseline carbon budget for the continental United States, i.e., circa late 1990s (Figure 3), can be constructed from NASA-CASA results in Table 1 and related studies [*Potter et al.*, 2003; *U.S. Department of Agriculture*, 2004]. In summary, net ecosystem carbon sinks (photosynthesis minus total respiration) in this budget are typically small, relative to annual U.S. fossil fuel–related carbon emissions. Carbon pool sizes in live terrestrial biomass are approximately two-thirds the size of woody litter and surface soil pools.

The carbon balance of terrestrial ecosystems may become increasingly susceptible to baseline pool declines with climate warming [*Zeng et al.*, 2004]. Large areas of the Pacific and Rocky Mountain regions of the

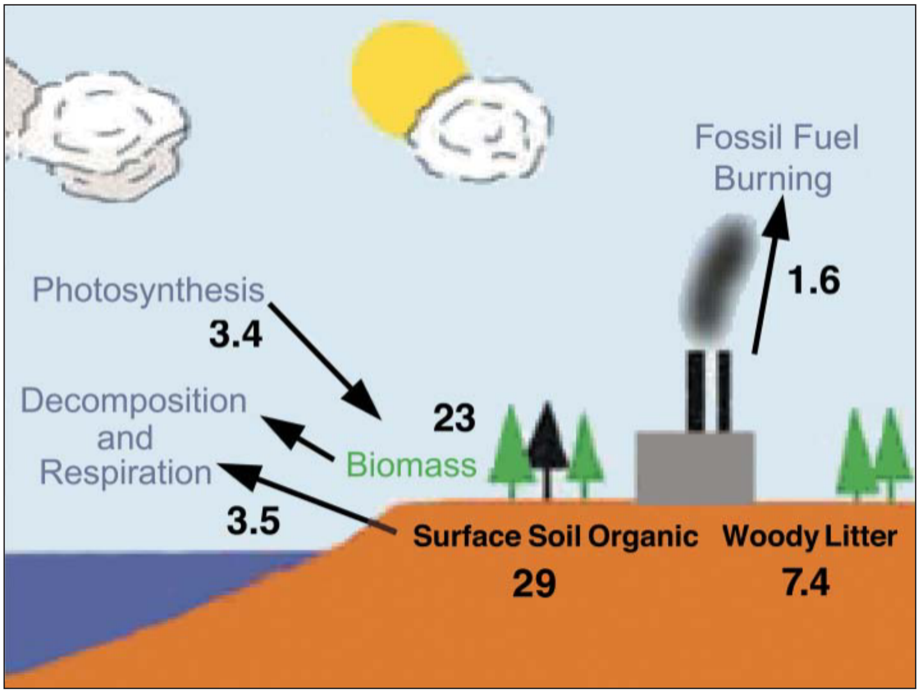

Fig. 3. Reconstructed carbon budget for the continental U.S., circa late 1990s. Pool and flux values are derived from Table 1 and U.S. Department of Agriculture *[2004]. Arrows represent annual fluxes. All values are petagrams of carbon. Original color image appears at the back of this volume.*

country may have recently lost carbon from baseline pools, possibly due to disturbances combined with variable climate patterns. Protection of woody litter and surface soil pools of carbon that have been accumulated over previous decades may be enhanced by a better understanding of the mechanisms of sequestration.

Because natural disturbance events or improper management can release terrestrial carbon rapidly, the stability of large carbon reservoirs in ecosystems deserves concerted research efforts under the North American Carbon Program, a program sponsored by the U.S. government and devoted to planning and implementing carbon sequestration and climate change impacts on the carbon cycle. Satellite remote sensing provides the level of spatial detail to uniquely support these research programs and management decisions. Additional reports of the CASA model are available online at http://geo.arc.nasa.gov/sge/casa/ as part of NASA's Carbon Query and Evaluation Support Tools (CQUEST) project.

References

Cox, P. M., R. A. Betts, C. D. Jones, S. A. Spall, and I. J. Totterdell (2000), Acceleration of global warming feedbacks due to carbon-cycle feedbacks in a coupled climate model, *Nature, 408,* 184–187.

Friedl, M. A., et al. (2002), Global land cover mapping from MODIS: Algorithms and early results, *Remote Sens. Environ., 83,* 287–302.

Geider, R., et al. (2001), Primary productivity of planet Earth: Biological determinants and physical constraints in terrestrial and aquatic habitats, *Global Change Biol., 7,* 849–882.

Hicke, J. A., G. P. Asner, J. T. Randerson, C. J. Tucker, S. Los, R. Birdsey, J. C. Jenkins, C. Field, and E. Holland (2002), Satellite-derived increases in net primary productivity across North America, 1982–1998, *Geophys. Res. Lett., 29*(10), 1427, doi:10.1029/2001GL013578.

Kittel, T. G. F., et al. (2000), The VEMAP Phase 1 database: An integrated input dataset for ecosystem and vegetation modeling for the conterminous United States, [CD-ROM], Natl. Cent. for Atmos. Res., Boulder, Colo. (Available at http://www.cgd.ucar.edu/vemap/)

Potter, C., S. Klooster, R. Myneni, V. Genovese, P. Tan, and V. Kumar (2003), Continental scale comparisons of terrestrial carbon sinks estimated from satellite data and ecosystem modeling 1982-98, *Global Planet. Change, 39,* 201–213.

Potter, C., P. Tan, V. Kumar, C. Kucharik, S. Klooster, V. Genovese, W. Cohen, and S. Healey (2005), Recent history of large-scale ecosystem disturbances in North America derived from the AVHRR satellite record, Ecosystems, doi:10.1007/s10021-005-0041-6.

Thornton, P. E., S. W. Running, and M. A. White (1997), Generating surfaces of daily meteorological variables over large regions of complex terrain, *J. Hydrol., 190,* 214–251.

U.S. Department of Agriculture (2004), National report on sustainable forests, 2003, *Rep. FS-766,* For. Serv., Washington, D. C. (Available at http://www.fs.fed.us/research/sustain/)

Zeng, N., H. Qian, E. Munoz, and R. Iacono (2004), How strong is carbon cycle–climate feedback under global warming?, *Geophys. Res. Lett., 31,* L20203, doi:10.1029/2004GL020904.

Author Information

Christopher Potter, NASA Ames Research Center, Moffett Field, Calif.; E-mail: cpotter@mail.arc.nasa.gov; Steven Klooster, California State University, Monterey Bay, Seaside; Ramakrishna Nemani, NASA Ames Research Center; Vanessa Genovese, California State University; Seth Hiatt, San Jose State University and Education Associates, Moffett Field, Calif.; Matthew Fladeland, NASA Ames Research Center; and Peggy Gross, California State University