

An atmospheric perspective on North American carbon dioxide exchange: CarbonTracker

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We present an estimate of net CO₂ exchange between the terrestrial biosphere and the atmosphere across North America for every week in the period 2000 through 2005. This estimate is derived from a set of 28,000 CO₂ mole fraction observations in the global atmosphere that are fed into a state-of-the-art data assimilation system for CO₂ called CarbonTracker. By design, the surface fluxes produced in CarbonTracker are consistent with the recent history of CO₂ in the atmosphere and provide constraints on the net carbon flux independent from national inventories derived from accounting efforts. We find the North American terrestrial biosphere to have absorbed -0.65 PgC/yr (1 petagram = 10^{15} g; negative signs are used for carbon sinks) averaged over the period studied, partly offsetting the estimated 1.85 PgC/yr release by fossil fuel burning and cement manufacturing. Uncertainty on this estimate is derived from a set of sensitivity experiments and places the sink within a range of -0.4 to -1.0 PgC/yr. The estimated sink is located mainly in the deciduous forests along the East Coast (32%) and the boreal coniferous forests (22%). Terrestrial uptake fell to -0.32 PgC/yr during the large-scale drought of 2002, suggesting sensitivity of the contemporary carbon sinks to climate extremes. CarbonTracker results are in excellent agreement with a wide collection of carbon inventories that form the basis of the first North American State of the Carbon Cycle Report (SOCCR), to be released in 2007. All CarbonTracker results are freely available at <http://carbontracker.noaa.gov>.

carbon cycle | greenhouse gases | data assimilation | biogeochemistry | atmospheric composition

Projections of future CO₂ levels in the atmosphere and the associated climate forcing, as well as our ability to control CO₂ levels, depend substantially on our scientific understanding of the natural carbon cycle. Its current capacity to absorb close to half of the carbon released from fossil fuel burning is not guaranteed to grow along with rapidly rising man-made emissions or to even continue at its present-day magnitude. Moreover, natural emissions themselves might increase as a result of already observable rapid warming in parts of the Arctic (1), where large carbon reservoirs are buried beneath the permafrost. Major national and international programs to study the carbon cycle are therefore underway.

The National Oceanic and Atmospheric Administration's (NOAA's) Earth System Research Laboratory (ESRL) monitors CO₂ in the atmosphere as a contribution to the North American Carbon Program (NACP) (2). Mole fractions of CO₂ are determined with an accuracy of 0.1 parts per million (ppm) from surface air samples collected around the globe and from tall towers and small aircraft in North America. These measurements form a record of integrated net CO₂ exchange from multiple processes, geographic areas, and times.

In addition, carbon exchange is monitored locally (≈ 1 km²) from a worldwide collection of surface flux measurements in different ecosystems and through periodic inventories of carbon in oceans, forests, and soils. The latter provide long-term constraints on the size of the different carbon pools. Monitoring of the carbon cycle through satellites mostly targets specific processes such as biomass burning, land-use change, or seasonal plant growth. Direct satellite observations of CO₂ are available already for the upper troposphere (3), whereas near-surface CO₂ from space will become available within several years to augment the current efforts.

To integrate this diversity of data into a consistent estimate of surface CO₂ exchange, the NOAA ESRL has built a new data assimilation system called CarbonTracker. It is used to retroactively analyze (reanalyze) the recent flux history of CO₂, using a state-of-the-art atmospheric transport model coupled to an ensemble Kalman filter. Currently, CarbonTracker assimilates only atmospheric CO₂ mole fractions, but efforts to expand it to assimilate observations of other trace gases in the atmosphere (¹³CO₂, ¹⁴CO₂, CH₄) and other observation types (eddy-flux measurements, satellite radiances) are underway. Specifically, such observations could facilitate attribution of carbon fluxes to specific processes such as fossil fuel burning, biomass burning, or agricultural food and biofuel production.

One of the main innovations in CarbonTracker is the use of daily CO₂ values derived from continuous observations from a network of tall towers. These data were not available in similar previous studies (4–7) but are potentially highly informative on regional exchange patterns because they represent direct samples of the resulting strong gradients in space and time. The ability to use these data comes from the improved skill of our atmospheric transport model, the efficiency of the ensemble Kalman filter in solving large optimization problems, and the inclusion of subdaily variability in the surface flux models we try to optimize.

In this work, we introduce CarbonTracker and analyze the recent flux history it produces. We compare its regional estimates for North America with an independent “bottom-up” estimate that is part of the State of the Carbon Cycle Report (SOCCR) (8). This document, created as part of the U.S.

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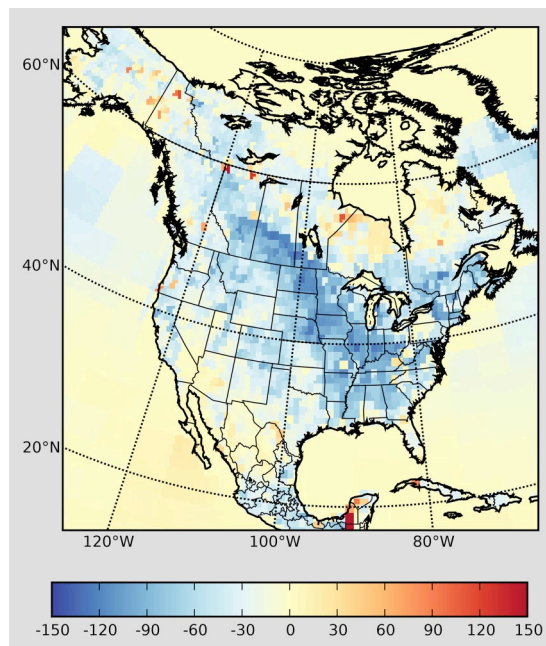


Fig. 1. Mean net terrestrial and oceanic flux (NEP plus fires; no fossil fuel emissions included) for the period 2001–2005 estimated from our system. Units are $\text{gC}/\text{m}^2/\text{yr}$. Note that the flux patterns at $1^\circ \times 1^\circ$ shown are the combination of 25 parameters optimized against atmospheric observations and $1^\circ \times 1^\circ$ fluxes from mechanistic models. See Eq. 1 and the text for more details.

sensitivity range. The uncertainty estimate is discussed in more detail in *SI Appendix*.

Annual Mean Fluxes

The 5-yr annual mean pattern of Net Ecosystem Production (NEP) derived from CarbonTracker is shown in Fig. 1. This represents the terrestrial part of the carbon cycle including fires but without the large fossil fuel emissions. The pattern of uptake is consistent with previous estimates of the North American carbon fluxes. Several factors influence the terrestrial CO_2 sink, but land-use history has been identified as the major determinant of regional terrestrial uptake (17–20). Large sinks can be found, for instance, in forests recovering from logging in the past century, as well as on abandoned agricultural lands recovering from past carbon losses. Increased fire suppression and changes in agricultural methods have also led to increased carbon storage in the soils and biosphere. These factors combined may be the cause of the strong uptake we calculate over the East Coast of the United States, in the Canadian coniferous forests, and across the grass and croplands of the Midwest.

A quantitative breakdown of this map by ecosystem type is shown in Fig. 2. We estimate total uptake in North America at $-0.65_{-1.01}^{+0.40}$ PgC/yr (1 petagram = 10^{15} g), with the majority of the sink in regions dominated by forest–field complexes ($-0.23_{-0.33}^{+0.10}$ PgC/yr), coniferous forests ($-0.16_{-0.38}^{+0.05}$ PgC/yr), croplands ($-0.11_{-0.12}^{+0.03}$ PgC/yr), and grasslands and shrubs ($-0.10_{-0.10}^{+0.0}$ PgC/yr). These estimates compare well with the SOCCR totals of -0.681 PgC/yr of absorption by the biosphere, of which -0.383 PgC/yr occurs in forests. Uncertainty on the SOCCR estimates is also close to 50%, making the good correspondence of the means somewhat fortuitous. A sink of -0.120 PgC/yr in the SOCCR inventory due to woody encroachment (described as invasion of woody plants into abandoned grass land or forests into shrub land) is not readily compared with any of our ecosystems, but the -0.10 PgC/yr sink found over grassland and

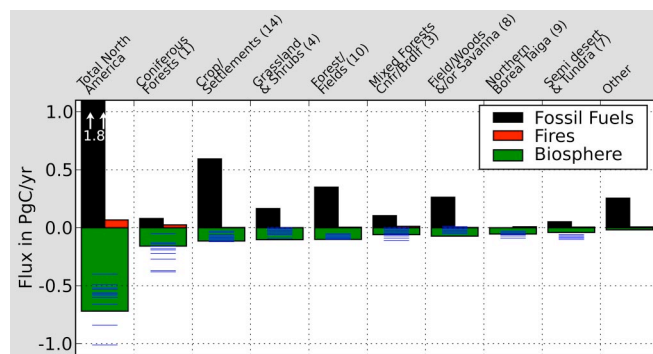


Fig. 2. Annual mean flux per ecoregion within North America for the period 2001–2005 estimated from our system. Black bars are the prescribed fossil fuel fluxes, red bars are the prescribed fire fluxes, and green bars are the estimated biological fluxes. Units are PgC/yr for each ecoregion. Blue horizontal lines denote the range of values found in a set of sensitivity experiments conducted for the year 2001 to determine the uncertainty. The labels refer to ecosystem types according to ref. 16 (<http://cdiac.ornl.gov/ftp/ndp017>). See text for more details.

shrubs might be part of this. However, more detailed comparisons with woody encroachment estimates are needed to complete this picture.

Large net uptake seen in areas dominated by croplands (-0.11 PgC/yr) may be due to the “atmospheric view” we take with CarbonTracker. Over agricultural lands, our system sees strong CO_2 uptake during the growing season but a much smaller return flux from respiration during the non-growing season. The difference can be explained by harvesting of crops and their subsequent transport, which is a substantial term in the carbon budget (21). The harvested crops are returned to the atmosphere after consumption spread across the country as a much smaller source per unit area. Because CarbonTracker was not built to keep track of lateral transport, this source is most likely assigned to regions with large population densities, whereas croplands remain annual mean net absorbers of carbon in the Midwest even though the soil carbon accumulation over these areas is thought to be small (22).

Similarly, it can be argued that lateral transport of wood-derived products and agricultural products for the international market, and carbon dissolved in river streams should be subtracted from the estimated net-absorption to yield the net CO_2 sink of North America. Although this carbon [total of ≈ 0.16 PgC/yr (19, 23, 24)] is removed from the atmosphere over North America and stored in other reservoirs, the longer-term stability of such reservoirs is hard to estimate and therefore questionable as a continental carbon sink.

Year-to-Year Variations

Year-to-year variations in the terrestrial carbon budget depend on climate variations that alter growing season length, regional temperatures, and moisture conditions (19, 25, 26). Through such mechanisms, a widespread drought over Europe in 2003 appears to have caused a reduction in CO_2 uptake of nearly 0.5 PgC/yr (27). As markets develop for the trading of CO_2 emissions, such anomalies represent multiple billions of dollars change in the continent’s carbon budget; hence the need to monitor them closely.

In our 5-yr estimate, 2002 stands out as a particularly low net uptake year (-0.32 PgC/yr) in North America, with only about half of the sink of the other years (Fig. 3). This phenomenon is apparent in both the temperate (-0.32 PgC/yr) and boreal (0.0 PgC/yr) zones and seems unrelated to emissions from fires in 2002 [≈ 0.065 PgC across North America (28)]. This suggests that the balance of

13. Peters W, Miller JB, Whitaker J, Denning AS, Hirsch A, Krol MC, Zupanski D, Bruhwiler L, Tans PP (2005) *J Geophys Res Atmos* 110:JD006157.
14. Xiao X (2007) *J Geophys Res Atmos* 112:JD07303.
15. Peylin P, Baker D, Sarmiento J, Ciais P, Bousquet P (2002) *J Geophys Res Atmos* 107:JD000857.
16. Olson JS, Watts JA, Allison LJ (1985) *Technical Report NDP-017* (Oak Ridge National Laboratory, Oak Ridge, TN).
17. Houghton RA, Hackler JL (1999) *Global Change Biol* 5:481–492.
18. Caspersen JP, Pacala SW, Jenkins JC, Hurtt GC, Moorcroft PR, Birdsey RA (2000) *Science* 290:1148–1151.
19. Pacala SW, Hurtt GC, Baker D, Peylin P, Houghton RA, Birdsey RA, Heath L, Sundquist ET, Stallard RF, Ciais P, *et al.* (2001) *Science* 292:2316–2320.
20. Hurtt GC (2002) *Proc Natl Acad Sci USA* 99:1389–1394.
21. Ciais P, Bousquet P, Freibauer A, Naegler T (2007) *Global Biogeochem Cycles* 21:GB002741.
22. US Environmental Protection Agency (2005) *Report 430-R-05-003* (US Environmental Protection Agency, Washington, DC).
23. Masera OR (1997) *Clim Change* 35:265–295.
24. Skog KE (2004) *Environ Manage* 33:S65–S73.
25. Zeng N, Mariotti A, Wetzel P (2005) *Global Biogeochem Cycles* 19:GB002273.
26. Chen JM, Chen B, Higuchi K, Liu J, Chan D, Worthy D, Tans P, Black A (2006) *Geophys Res Lett* 33:GL025919.
27. Ciais P, Viovy N, Chevallier F, De Noblet N, Friend AD, Friedlingstein P, Reichstein M, Manca G, Papale D, Valentini R, *et al.* (2005) *Nature* 437:529–533.
28. van der Werf GR, Randerson JT, Giglio L, Collatz GJ, Kasibhatla PS, Arellano AF, Jr (2006) *Atmos Chem Phys* 6:3423–3441.
29. Zeng N, Qian HF, Rödenbeck C, Heimann M (2005) *Geophys Res Lett* 32:GL024607.
30. Stephens BB, Gurney KR, Tans PP, Sweeney C, Peters W, Bruhwiler L, Ciais P, Ramonet M, Bousquet P, Nakazawa T, *et al.* (2007) *Science* 316:1732–1735.
31. Yang Z, Washenfelder RA, Keppel-Aleks G, Krakauer NY, Randerson JT, Tans PP, Sweeney C, Wennberg PO (2007) *Geophys Res Lett* 34:GL029742.
32. Bosch H, Toon GC, Sen B, Washenfelder RA, Wennberg PO, Buchwitz M, de Beek R, Burrows JP, Crisp D, Christi M, *et al.* (2006) *J Geophys Res Atmos* 111:D23302.
33. Washenfelder RA, Toon GC, Blavier JF, Yang Z, Allen NT, Wennberg PO, Vay SA, Matross DM, Daube BC (2006) *J Geophys Res Atmos* 111:D22305.
34. Rayner PJ, O'Brien DM (2001) *Geophys Res Lett* 28:175–178.
35. Houweling S, Breon FM, Aben I, Rödenbeck C, Gloor M, Heimann M, Ciais P (2004) *Atmos Chem Phys* 4:523–538.