PERSPECTIVES: CLIMATE CHANGE

Variable Carbon Sinks

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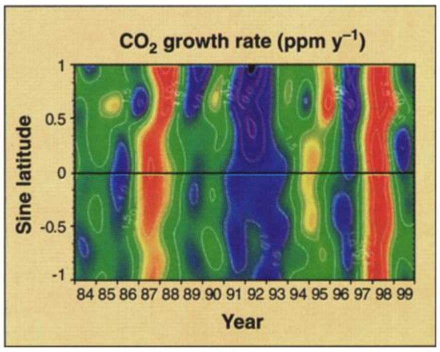
Less than half of the CO_2 released to the atmosphere by combustion of fossil fuels and from deforestation remains in the atmosphere. The remainder is sequestered in oceanic and terrestrial repositories called sinks. During the 1990s, these sinks absorbed 4 to 5 Pg C year^{-1}, but the location and magnitude of the sinks are highly uncertain. It is difficult to identify CO_2 sinks from direct observations because of the heterogeneity of the land surface, the variability of the oceans, and the many processes that cycle carbon in the terrestrial and oceanic reservoirs. Extrapolation from the very sparse site-specific measurements to a regional long-term sink is difficult because of incomplete spatial and temporal information and inadequate accounting for the underlying processes. Inversion studies, which exploit variations in atmospheric CO_2 concentrations to infer the regional magnitudes of the net CO_2 exchange (*1*, *2*), circumvent these difficulties. There is a concentration gradient of 3 to 4 parts per million by volume (ppmv) from the Northern to the Southern Hemisphere because much of the CO_2 is emitted in the Northern Hemisphere. The specific characteristics of this gradient indicate that there is a land sink in the northern mid-latitudes, which has amounted to 1.5 ± 0.5 Pg C year^{-1} in recent decades. In addition, Fan *et al.* (*3*) interpreted the small (<0.5 ppmv) CO_2 difference between the North Atlantic and North Pacific to mean that, for 1988–92, this Northern Hemisphere land sink was located principally in North America south of 51°N, with little contribution from Eurasia. The east-west partitioning of the Northern Hemisphere land sink has fueled much debate (*4*, *5*) and research.

On page 1342 of this issue, Bousquet *et al.* (*6*) report the most comprehensive inversion study to date. The authors calculate the magnitude of the CO_2 sink in each of four ocean and four land regions for every month since 1980. As in all previous inversion calculations, the contributions from fossil fuel combustion to atmospheric CO_2 variations are calculated separately and subtracted a priori from the CO_2 observations.

It is tempting to immediately compare the North American and Eurasian distribution of the land sink predicted by their analysis with that from other studies. Bousquet *et al.* warn against this temptation, because the mean east-west sink partitioning is not a robust result of the inversion. This conclusion is based on the extensive sensitivity studies carried out by the authors and an intercomparsion of atmospheric circulation models used for the inversions (*7*, *8*).

What is robust and exciting in this report are the year-to-year fluctuations in the regional CO_2 sinks (see the figure). [The authors plot in the figures the anomalous fluxes, which are monthly departures from the 20-year regional means reported in the supplementary material (*9*).] The global interannual variations in terrestrial fluxes are twice as large as their oceanic counterparts. The North American sink is more variable than the Eurasian sink, a result that is probably an artifact of the large area over which Eurasian fluxes have been averaged. The fluctuations of the North American sink are as large as the discrepancy between different inversion estimates of the mean sink strength (*2*, *3*). According to Bousquet *et al.*'s estimate of the mean sink strength, North America would have acted as a net source (on top of fossil fuel emissions) in 1990 and as a net sink (comparable in strength to that of Eurasia) in 1993. In contrast, with Fan *et al.*'s mean sink strengths, North America would have been neutral in terms of net carbon exchange in 1990 but would have been an implausibly large carbon sink in 1993.



Where are the sinks? Temporal and latitudinal variations in the increase of atmospheric CO_2. The cooler colors (green, blue, and violet) represent periods of lower than average growth rates, and the warmer colors (yellow, orange, and red) represent high growth rate periods. The figure is derived from measurements of thousands of air samples collected at the NOAA Climate Modeling and Diagnostics Laboratory (CMDL) cooperative sampling network sites (www.cmdl.noaa.gov) and is the subject of Bousquet *et al.*'s inversion study (*6*).

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Temperature and precipitation anomalies influence the rates of photosynthesis, decomposition, disturbance, and other processes that cycle carbon between terrestrial ecosystems and the atmosphere. Regional fluxes derived from inversions can therefore be related to climate perturbations (*10*, *11*). Bousquet *et al.* draw attention to the terrestrial tropics. The tropical land sink inferred by Bousquet *et al.* includes the regional CO_2 emission from deforestation (1.5 to 2 Pg C year^{-1}). When the deforestation source is accounted for, this yields a tropical sink that is as large as, or larger than, the total mid-latitude land sink. From 1980 to 1989, the CO_2 flux fluctuations of tropical land areas dominate the global flux variability. These tropical fluxes fluctuate by 2 to 3 Pg C year^{-1}, comparable to the decadal average of the total global (land and ocean) sink.

The implications of this study for carbon science and policy are immense. The large interannual variations in the net flux will make it difficult to determine whether an area acting as a carbon sink over 5 or so years is likely to remain a net sink over a decade or longer. This adds a temporal dimension to ongoing efforts to obtain convergence between "bottom-up" field measurements of net CO_2 fluxes and "top-down" inferences from atmospheric CO_2 variations.

The duration of a carbon sink is an important, yet until now not centerstage, consideration in the design of strategies to manage carbon storage on land and of protocols to assess their efficacy. Furthermore, the observation that the interannual fluctuations and the decadal average are of comparable magnitude raises the question of whether the land sink will remain stable in the face of a long-term change in climate and climate variability. A "runaway" net carbon source/sink anomaly may alter the growth of atmospheric CO_2 and hence the rate of climate change.

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