Carbon cycle conundrums

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What will control future rates of climate change? The carbon cycle is the largest contributor to anthropogenic climate change, yet despite decades of research (1), significant mysteries about its behavior remain. Global analyses show that the Earth system absorbs approximately half of anthropogenic fossil fuel emissions. This uptake is partitioned between absorption by the oceans and storage in terrestrial ecosystems. Uptake by the Earth system reduces the climate effects of emitted CO_2 to approximately half of what would occur without sinks. Models tend to project sinks, particularly terrestrial sinks, into the future based on assumptions about the behavior of mechanisms derived from small plot or laboratory studies.

The observational record is now long enough and rich enough to provide strong constraints on both the human and the biogeochemical behavior of the carbon cycle. In this issue of PNAS, Canadell *et al.* (2) report an increase in the rate of increase in CO_2 in the atmosphere (henceforth called the "growth rate"). They analyze the historical carbon record and industrial and biogeochemical causes to changes in its behavior over time. Industrial growth is responsible for ≈65% of the change in the growth rate, 17% is caused by increasing carbon intensity (fossil fuel use/gross world product), and 18% is caused by reduced sinks in the Earth system. The reduction over time of the efficiency of the sinks is of great concern because it implies a weakening in the ability of the Earth system to mitigate the effects of fossil fuel emissions and a potential positive feedback that may strengthen in the future.

Behavior of Sinks

A progressive weakening of Earth system sinks has long been of concern (3), but until recently, insufficient information has existed to diagnose the behavior of the carbon sinks over time. The fraction of fossil fuel-derived CO_2 remaining in the atmosphere (the "airborne fraction") has increased over the past 50 years, strongly suggesting that the ocean and terrestrial sinks are not keeping up with increasing emissions. This behavior has to form a strong constraint on any simulation of the future. For example, a model that did not replicate the trend in the airborne fraction will probably not produce a skillful projection of the future behavior of the carbon–climate system. Canadell *et al.* (2) note that of 11 current coupled carbon climate models, 9 simulate a decrease in sinks over the period of historical record, consistent with observations, but that observed trend is larger than the simulated. This finding implies that the carbon cycle has changed faster than today's models simulate, with implications that positive carbon-cycle feedbacks may emerge sooner than predicted in the future.

Against this background, what to do we know of mechanisms governing these large-scale trends? Focusing on terrestrial systems, which are less well understood than the oceans, a number of issues are currently under intense investigation. The initial hypothesis for the primary mechanism controlling the terrestrial response to global change was that increasing atmospheric CO_2 would fuel an increase in plant growth (CO_2 fertilization). This assumption led to projecting terrestrial sinks that would scale with increasing atmospheric CO_2 proportionately. In the 1990s, controversy over the dominance of this mechanism emerged (4, 5), and recent literature has tended to downplay its importance (6). More recent literature has tended to assume that recovery from historic land use was the dominant process leading to terrestrial carbon uptake. Northern Hemisphere forests harvested or cleared in the early industrial period are now regrowing and accumulating carbon (5). This Northern Hemisphere recovery is in contrast to emissions from contemporary forest harvest, largely in the tropics, where some recent work suggests even higher rates than the canonical estimates (7).

The emerging view thus suggests a terrestrial biosphere losing carbon in the tropics and gaining carbon in the Northern Hemisphere with the net of the two favoring accumulation. Two recent articles call this view into question. Jacobson *et al.* (8) used global atmosphere and ocean CO_2 data to perform an inverse estimate of global sources and sinks. Traditional inverse analysis techniques (9) tend to show Northern Hemisphere sinks but lack resolution in the tropical regions. Comparisons of inverse models show a wide range of results in the tropics (10). Jacobson *et al.* found, in contrast to most atmosphere-only inversions, a strong tropical source, making the existence of a strong tropical CO_2 fertilization sink in the tropics unlikely.

Standard inversions use atmospheric CO_2 concentrations and only measurements from the surface. Stephens *et al.* (11) compiled vertical profiles of CO_2 measured with aircraft and compared them with simulated vertical profiles from the models described by Gurney *et al.* (10). Stephens *et al.* found that the models from the Gurney set that best matched observations consistently suggested a pattern of fluxes quite different from the canonical view; rather, they found that these models suggested weaker Northern Hemisphere uptake than the mainstream view and also suggested uptake in the tropics. The Stephens *et al.* results suggest that uptake in the tropics balances deforestation emissions or even causes a small net sink in the tropics. This result is important because, first, it challenges the traditional view of the dominance of Northern Hemisphere sinks, and, second, it reopens the discussion of CO_2 fertilization because that is the most likely mechanism for a tropical terrestrial sink. Together, the results from Jacobson *et al.* (8) and Stephens *et al.* (11) open up questions in an area where consensus seemed to be emerging.

Sensitivity to Warming Temperatures

Another long-running research area has been the sensitivity of the carbon cycle to warming temperatures. Warmer temperatures can stimulate both photosynthesis and respiration and so increase both carbon uptake and release (3). Most current process models suggest that warming conditions weaken terrestrial sinks globally, although they may strengthen uptake in colder high-latitude regions (12). Recent results suggest that changes to water balance may be more important than temperature and that the main effect of temperature may be via its effects on water stress (13, 14).

An indirect effect of warming is to lengthen the growing season often. This has been assumed to be a negative feedback (i.e., longer growing seasons should increase carbon uptake) (15). Recent evidence suggests that in many

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environments, longer growing seasons result in lengthening seasonal drought conditions and reduce carbon uptake, which has been shown in both large-scale (14) and local (12) studies. Does a changing growing season mean more or less carbon uptake? The answer is still unknown, but the simple assumption that longer growing seasons equal more carbon uptake seems less and less likely to be universal.

Finally, temperature affects the frequency of insect outbreaks and wildfire also seem to be influencing terrestrial carbon responses to climate, possibly dominating over the physiological responses. Projecting the future of terrestrial carbon uptake requires simulation of the effects of temperature, precipitation, and the precipitation–evapotranspiration balance, challenging the skill of both the carbon and the climate components of coupled models.

Key Questions

Key questions thus remain about the contemporary carbon cycle and the mechanisms causing its observed behavior. Although we have learned a great deal about the carbon cycle, the scientific community is still limited in its ability to make confident predictions about the likely response of the carbon cycle to global environmental change. Questions emerge about the likely roles of CO_2 fertilization versus land-use change, about temperature versus moisture changes, and about the potential wildcard effects of insects, plant disease, and wildfire. These processes can be studied at their natural local scale, but aggregating their effects to the global scale is extremely difficult. The fact that different regions can experience different climate changes (e.g., some regions getting drier, others wetter) and varying land-use changes (deforested versus regrowing areas) makes this scaling all the more difficult. Getting global phenomena right, like the observed change in the airborne fraction, is critical for testing models. Purely local or process-level validation is not enough because of the great variety of local responses.

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When adding up idiosyncratic regional responses over the globe, requiring the sum to match an observed trend, in this case the change in the airborne fraction, provides a critical additional constraint. Progress in improving predictive capability seems to occur when models are challenged to reproduce both small-scale and global-scale phenomena. I have focused on uncertainties in 18% of the problem, the part of the change in the growth rate of CO_2 that is caused by Earth system responses, and mainly on the terrestrial part of that 18%. Similar uncertainties exist in the understanding of the 82% dominated by human fossil fuel use, the human side of the equation. The increase in carbon intensity, despite growing concern about warming and improvements in technology, is of special concern. Opportunities for testing theories about technology and the economy against the emergent behavior of the global system also exist. Canadell *et al.* (2) provide a series of global benchmarks that should be explained as a precondition for believable projections of the human impact on the carbon–climate system.

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