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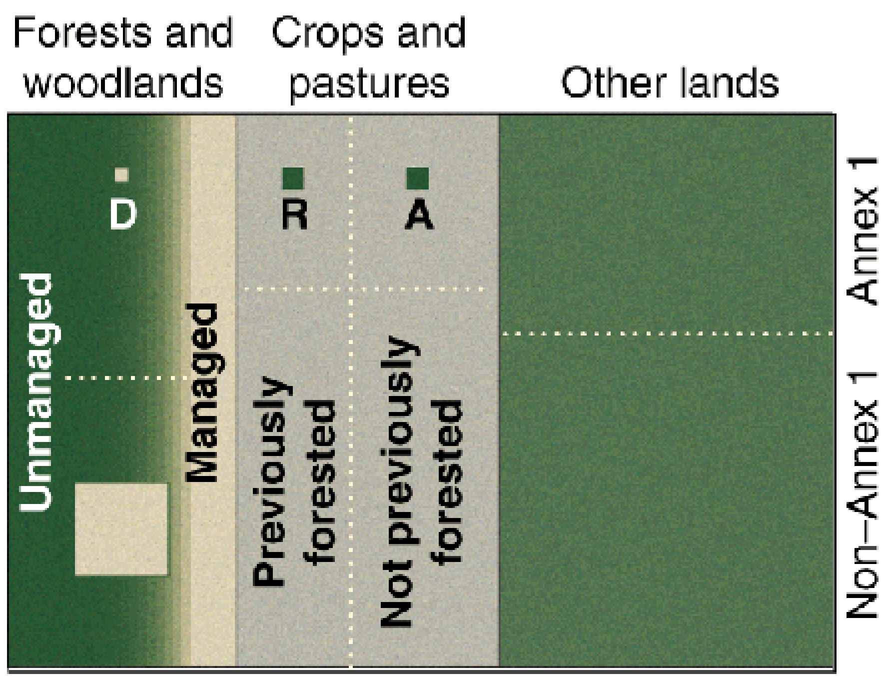
In all, 174 countries have ratified the United Nations Framework Convention on Climate Change (UNFCCC), which aims at "the stabilization of greenhouse gases in the atmosphere at a level that will prevent dangerous anthropogenic interference with the climate system." In December 1997, the signatory nations agreed to the Kyoto Protocol, which sets out the first steps toward achieving this goal by reducing fossil fuel emissions and the net emissions from some terrestrial ecosystems in developed countries (known as Annex 1 countries in the protocol).

According to the Kyoto Protocol, Annex 1 countries can reduce emissions by limiting fossil fuel consumption or by increasing net carbon sequestration in terrestrial carbon sinks. The inclusion of terrestrial carbon sources and sinks in a legally binding emissions reduction framework is significant (1). However, it creates a number of problems that, if not corrected, will seriously limit the protocol's effectiveness as follows:

- The protocol limits the allowable terrestrial sources and sinks of carbon to strictly defined cases of "afforestation, reforestation and deforestation" (2) since 1990 (the "Kyoto forests"; see figure below). There are, however, many more ways in which appropriate management of the terrestrial biosphere, especially of soils, can substantially reduce the buildup of atmospheric greenhouse gases.

- The 1990 estimates of carbon emissions, which form the baseline for all emission reduction targets of the protocol, exclude sinks to terrestrial ecosystems. Nevertheless, sources and sinks from the Kyoto forests are to be counted as part of a country's efforts to reduce emissions within the specified commitment period (2008 to 2012). This difference is referred to as the "gross-net disparity," and for some nations it serves to decrease the need for reductions in fossil fuel emissions to achieve targets.
- The protocol is not based on a full carbon budget [all components of all ecosystems (3)] applied continuously in time but instead applies a partial budget to discontinuous "commitment" periods. As a result, the protocol has created an opportunity for counterproductive actions that could actually increase cumulative emissions. For example, emissions associated with deforestation between commitment periods will not be counted. There are also many uncertainties about the relationship of forestry harvesting cycles to the definitions of afforestation, reforestation, and deforestation adopted in the protocol.

The effectiveness of the protocol can be greatly improved within the existing framework. Many details still remain to be decided by subsidiary bodies to the convention, including the Subsidiary Body on Scientific and Technical Advice, which is to meet in Bonn early in June 1998.



The Kyoto forests. The total land area of Earth is divided into three types of land cover. The deforested (D), reforested (R), and afforested (A) blocks are estimates, based on 1990–95 rates, of the areas that may be included as offsets to fossil fuel emissions under the Kyoto Protocol. The block in the lower left corner represents the area that will be deforested between 1990 to 2010 in non-Annex 1 countries if deforestation continues at 1990–95 rates.

The Terrestrial Carbon Budget

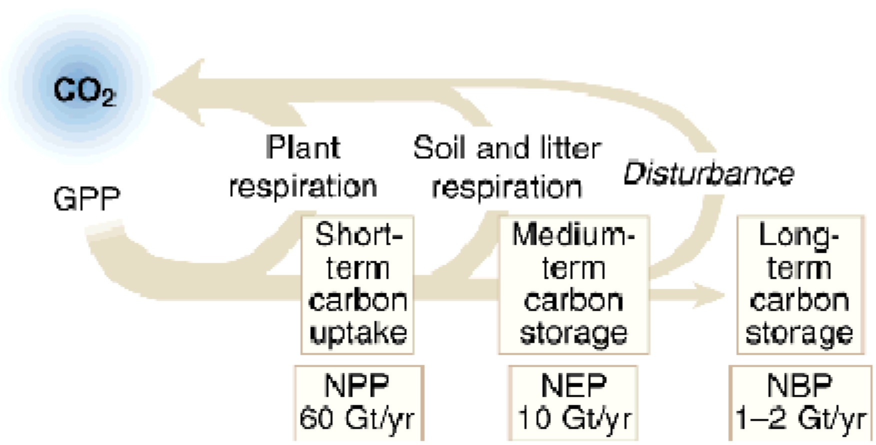
The increase in atmospheric CO_2, the main greenhouse gas, is driven by the emission of 5.5 gigatons (Gt) of carbon per year from fossil fuels and industrial activity (now 6.5 Gt per year) and an additional 1.6 Gt per year from deforestation (4, 5). Terrestrial ecosystems and oceans absorb some of these emissions, but on average 3.4 Gt of carbon accumulate in the atmosphere each year (6). The terrestrial absorption is the small difference between the large amounts of carbon exchanged between terrestrial ecosystems and the atmosphere (about 60 Gt of carbon per year in each direction). Currently, this difference results in a net terrestrial carbon sink of about 2 Gt per year.

Fossil fuel emissions are essentially irreversible, whereas terrestrial sinks are part of an active biological cycle, so that a substantial fraction of the fossil fuel carbon sequestered in terrestrial biosphere sinks during the next few decades is vulnerable to return to the atmosphere a century or so hence. Thus, terrestrial sinks are best viewed as important but temporary reservoirs that can buy valuable time to reduce industrial emissions, but they are not permanent offsets to these emissions.

Many processes that influence the net terrestrial sink are beyond direct human management, but some terrestrial systems can be managed to increase uptake and decrease emissions. Understanding the nature of terrestrial carbon sinks—their distribution, control, longevity, and reliability—requires a full-system carbon budget applied over large space and long time scales.

The Kyoto forests, consisting of post-1990 reforestation, afforestation, and deforestation in Annex 1 countries, are a small subset of the terrestrial carbon budget (see figure above). A full carbon budget applied to all land-use types would account for all potential terrestrial sinks and sources, not just those of the Kyoto forests, and would help identify other sinks that could be increased through management.

About 50% of the initial uptake of carbon through photosynthesis [gross primary production (GPP)] is used by plants for growth and maintenance (see figure, below). The remaining carbon is net primary production (NPP). Part of this is shed as litter and enters the soil, where it decomposes, releasing nutrients to the soil and CO_2 to the atmosphere. The remaining carbon after these emissions is net ecosystem production (NEP). Much of this is lost by nonrespiratory processes such as fire, insect damage, and harvest. The remaining carbon is called net biome production (NBP) (7). NBP is a small fraction of the initial uptake of CO_2 from the atmosphere and can be positive or negative; at equilibrium it would be zero. NBP is the critical parameter to consider for long-term (decadal) carbon storage.



Terrestrial carbon uptake and storage. The below-ground compartment (soils and roots) of terrestrial ecosystems is especially important. About two-thirds of terrestrial carbon is found below ground, and below-ground carbon generally has slower turnover rates than above-ground carbon. Thus, carbon storage can be maintained over longer periods of time. Below-ground carbon is normally more protected than above-ground carbon during fires and other disturbances and can contribute a large fraction to NBP.

Carbon Accounting Methodology

The Kyoto Protocol established the basis for a system of verifiable emission reduction targets by (i) introducing the concept that verifiable changes in carbon stocks in the land use and forestry sector could offset industrial emissions, (ii) allowing trading of carbon credits between Annex 1 countries (Joint Implementation), and (iii) allowing cooperation between Annex 1 and non-Annex 1 countries in reducing net emissions (Clean Development Mechanisms).

In our view, these steps will require three accounting systems: (i) national inventories that include full carbon budgets; (ii) a subset of this accounting system that assesses verifiable offsets and compliance with the protocol; and, we suspect, (iii) a new accounting system for carbon trading. These additional accounting systems should be logical subsets of the full carbon budget. They will be counterproductive if they incorporate misaccounting or introduce perverse incentives that are inconsistent with the goal of long-term stabilization of atmospheric CO_2 (UNFCCC, Article 2).

National Greenhouse Gas Inventories, which are estimates of gas sources and sinks prepared annually by each country as part of their obligations under the UNFCCC, will be the main accounting system for measuring both changes in the full carbon budget and verifiable changes in carbon stocks in afforested, reforested, or deforested areas during the commitment period as required by the Kyoto Protocol. Values for carbon stocks and their rate of change estimated from small patches of vegetation, plus detailed information on changes in vegetation cover and land conversion, often measured by remote sensing techniques (8), will be the basis for budget calculations. Changes in soil carbon associated with land-use changes (deforestation, cultivation, and so forth) can be large and should logically be included.

The protocol calls for emissions and sinks in the Kyoto forests to be "measured as verifiable changes in stocks in each commitment period." This clause needs to be clarified because it is unclear which stocks are included (for example, forest products or soil carbon), and differences in estimates of stocks made only 5 years apart may not be a sufficiently accurate way of measuring fluxes of carbon to the atmosphere without other types of supportive measurements.

There has been concern that the uncertainty in estimating carbon fluxes associated with land-use change and forestry is so large as to threaten the compliance process. In our view, these uncertainties can be reduced to acceptable levels with the application of appropriate inventory techniques. In addition, there has been rapid development over the past decade of quantitative techniques for measuring component fluxes and stocks of the carbon cycle, leading to a vastly improved understanding of the partitioning of carbon between oceans and land and among the various terrestrial sinks. In the context of the Kyoto Protocol, instrumental measurement of terrestrial carbon fluxes can provide independent estimates of changes in carbon stocks, as well as insights into the processes affecting full carbon budgets over wide spatial and long time scales.

At the scale of a vegetation patch (about 1 hectare), developments in eddy covariance make possible the continuous measurement (over times from minutes to years) of NEP. At landscape scales (1 to 100 km), measurements can be made of the convective boundary layer, which acts as an interface reservoir between the vegetation surface and the background atmosphere. At regional to global scales, networks measuring the long-term distribution of and trends in atmospheric CO_2 concentration, coupled with inverse modeling of atmospheric transport, give an estimate of NBP. Flux measurements (along with climate, soil, and physiological studies) and manipulative experiments are critical to identify mechanisms responsible for carbon uptake or loss and for long-term metabolic adjustments (for example, sink saturation).

Finally, ecosystem and biospheric models coupled with satellite remote-sensing data can be used as valuable tools to extrapolate flux and process measurements to the appropriate regional, national, and global scales. These methodologies will need to be applied to both managed (that is, the Kyoto forests) and unmanaged systems during long periods to account properly for interannual variability and to contribute to a full carbon budget.

Conclusions

A full carbon budget, over sufficient time scales to reflect changes in long-term carbon storage (that is, in NBP), is the appropriate basis for any accounting system for terrestrial carbon. Partial accounting systems, such as that described in the Kyoto Protocol, should be logical subsets of the whole-system approach. Eventually, all terrestrial ecosystems, both managed and unmanaged, should be included to recognize and potentially increase all terrestrial sinks, to minimize sources, and to avoid the surprise of large unanticipated releases of carbon from unmanaged systems.

A full carbon budget applied to contiguous commitment periods will discourage counterproductive actions that might arise from partial budget approaches applied to noncontiguous commitment periods.

An integrated system based on the monitoring of changes in carbon stocks and of direct flux measurements, and its improvement over the next decade, will further reduce the uncertainties in estimating carbon sources and sinks and therefore provide a verification tool for a full carbon budget.

Although terrestrial ecosystems can be managed to reduce carbon emissions and increase carbon sink size significantly, such increased carbon uptake can offset fossil fuel emissions only temporarily—on a time scale from decades to a century. Terrestrial carbon sinks are thus best viewed as buying valuable time to address the most significant anthropogenic perturbation of the carbon cycle—fossil fuel emissions.

References and Notes

1. *Greenhouse Gases Sink Approach of the Kyoto Protocol* (European Commission, DG XII/D, Brussels, Belgium, 1998).
2. Afforestation is establishing forests on previously nonforested land;reforestation is establishing forests on land previously forested;and deforestation is the removal of forest.
3. The comprehensive “net-net” approach of the Intergovernmental Panel on Climate Change.
4. Budget figures in this section are based on averages from 1980 to 1990.
5. Houghton R. A., Hackler J. L., ORNL/CDIAC-79, NDP-050 (Oak Ridge National Laboratory, Oak Ridge, TN, 1995), p. 144.
6. Schimel D. S., *Global Change Biol.**1***, 77 (1995).
7. Schulze E.-D., Heimann M., *Asian Change in the Context of Global Change*, , Galloway J. N., Melillo J., Eds. (Cambridge Univ. Press).
8. Copping P. R., Bauer M. E., *Remote Sens. Rev.**13***, 207 (1996).

9. We thank NASA, the European Commission DG XII, and the IGBP Secretariat for supporting our meeting of the IGBP Terrestrial Carbon Working Group on the terrestrial carbon cycle on 27 to 29 April 1998 in Stockholm, during which a first draft of this paper was written. Additional information is available at http://www.igbp.kva.se/.