The resulting change in the physical properties and shear strength of the hydrate-bearing sediment may encourage massive slope failure along low-angle detachment faults (*6*). Such slumping can pose a considerable hazard to petroleum drilling rigs and to undersea cables. In addition, extensive slope failures can conceivably release large amounts of methane gas into the seawater and atmosphere that could enhance greenhouse warming over the longer term.

Gas hydrate dissociation near the end of the last glacial period (about 18,000 years ago) may have been responsible for the rapid termination of the glacial episode (*7*). During the glacial period, the sea level fell by ~120 m, which lowered the hydrostatic pressure, leading to massive slumping that may have liberated substantial amounts of methane. This may in turn have triggered greenhouse warming and, possibly, a rapid deglaciation. Ice core records of glacial-interglacial periods from Greenland and Antarctica (*8*, *9*) show parallel temperature increases and rising concentrations of atmospheric methane and carbon dioxide. However, the temporal resolution of the records is not refined enough to determine whether the temperature rise caused hydrate dissociation and methane increase or vice versa (*9*). A decadal resolution (~50 years) will be necessary to understand the leads and lags.

The occurrence and stability of gas hydrates at oceanic depths of the continental slope and rise have led to the notion that we may be able to dispose of excess greenhouse gases, especially carbon dioxide, in the deep ocean as synthetic hydrates. Such sequestration of carbon dioxide would not be permanent because the hydrate on the sea floor would eventually be dissolved and dispersed in seawater. However, given the long time scales of ocean circulation, the large size of the oceanic reservoir, and the buffering effect of carbonate sediments, carbon dioxide in the form of solid hydrate may remain stable for hundreds to thousands of years (*10*).

Substantial uncertainty remains regarding the nature, formation, and location of the gas hydrate reservoirs—both in the sea and on land—and their energy and climate change potentials. To make meaningful estimates of their total volume on continental margins and in the permafrost, we need to know whether they are thinly dispersed in sediments or occur in substantial local concentrations. Seismic data from the Hydrate Ridge off the coast of Oregon suggest intricate plumbing systems and methane migration pathways within the hydrate stability zone and below (*11*). Disruptions in the BSR that correlate with the sea-floor morphology imply dissolution of hydrate in response to slumping and folding along this active margin. Modeling efforts suggest that advective processes and high methane flux through fault zones may be important for concentrating hydrate (*12*). Understanding of all these processes is still limited. We also need a better understanding of biological methane-forming activity under high pressure and the subsequent organic-matter decomposition associated with methanogenesis, which have to be factored into dynamic hydrate models. Finally, to appreciate the role of gas hydrates in global climate change, we need to have a better grasp of how much of the hydrate in the continental margins and the permafrost responds to oceanic and atmospheric temperature fluctuations. More importantly, we must understand the fate of the methane released from a hydrate source into the water column and the atmosphere. Studies of the geological records of past hydrate fields can also provide clues to their behavior and role in climate change.

Revival of interest in gas hydrates has opened a new frontier in ocean and Earth sciences that crosses many disciplinary boundaries. The next decade promises to be a challenging period to resolve the riddle of gas hydrates, their role in environmental change, and their potential as an energy resource.

References and Notes

1. B. U. Haq, *GSA Today* **8** (no. 11), 1 (1998).
2. F. S. Colwell *et al.*, *Eos* (*Spring Meet. Suppl.*) **80** (no. 17), S338 (1999).
3. K. A. Kvenvolden, in *Gas Hydrates, Relevance to World Margin Stability and Climatic Change*, J.-P. Henriet and J. Mienert, Eds. (Geological Society of London, 1998), pp. 9–30.
4. C. K. Paull *et al.*, *Proceedings of the Ocean Drilling Program, Leg 164* (Ocean Drilling Program, College Station, TX, 1996).
5. W. Zhang *et al.*, *Eos* (*Spring Meet. Suppl.*) **80** (no. 17), S337 (1999).
6. W. P. Dillon and C. K. Paull, in *Natural Gas Hydrates, Properties, Occurrence, Recovery*, L. L. Cox, Ed. (Butterworth, Woburn, MA, 1983), pp. 73–90.
7. C. K. Paull *et al.*, *Geophys. Res. Lett.* **18**, 432 (1991).
8. J. Jouzel *et al.*, *Nature* **364**, 407 (1993)
9. D. Raynaud *et al.*, in *Gas Hydrates, Relevance to World Margin Stability and Climatic Change*, J.-P. Henriet and J. Mienert, Eds. (Geological Society of London, 1998), pp. 327–331.
10. P. G. Brewer, G. Friederich, E. T. Peltzer, F. M. Orr Jr., *Science* **284**, 943 (1999).
11. A. Trehu *et al.*, in preparation.
12. J. N. Nimblett and C. D. Ruppel, *Eos* (*Spring Meet. Suppl.*) **80** (no. 17), S333 (1999).
13. Opinions expressed in this perspective are the author's and do not necessarily reflect those of the National Science Foundation.

PERSPECTIVES: BIOGEOCHEMICAL CYCLES

The Not-So-Big U.S. Carbon Sink

Christopher B. Field and Inez Y. Fung

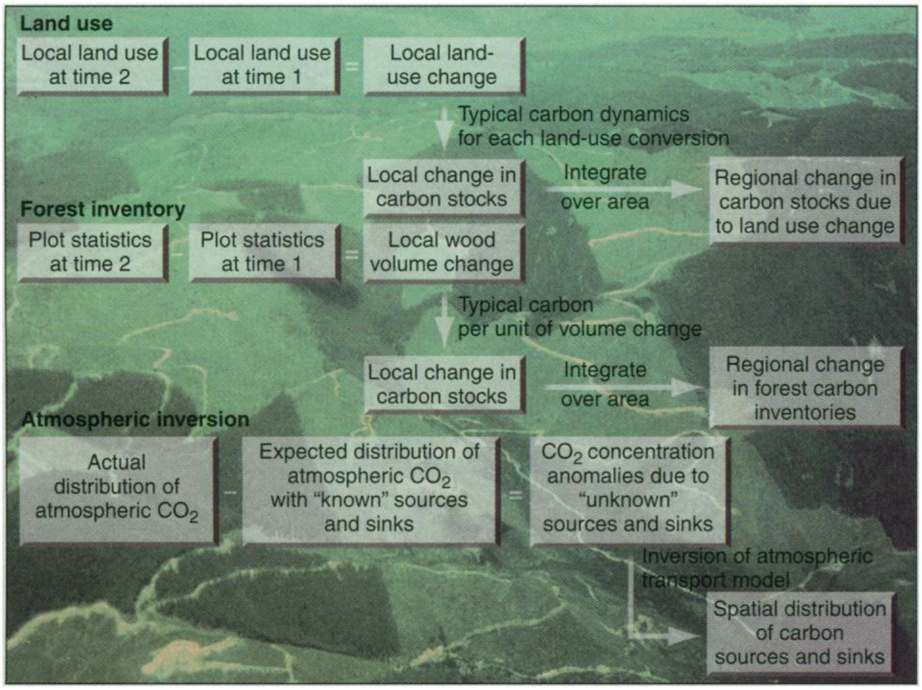
Less than half of the carbon emitted to the atmosphere through deforestation, fossil fuel combustion, and cement manufacture remains in the atmosphere. The remainder of the carbon emitted through these human activities is stored, at least temporarily, in carbon sinks in the oceans and in terrestrial ecosystems. Quantifying these sinks and understanding the underlying mechanisms are top priorities for understanding Earth's major biogeochemical cycles and for establishing how changes in their magnitude could affect the future trajectory of atmospheric CO_2 concentrations.

Enhanced online at www.sciencemag.org/cgi/content/full/285/5427/544

Measured atmospheric CO_2, ^{13}C, and O_2/N_2 distributions indicate that during the past two decades, a substantial fraction of the carbon sink has been on land, in the temperate and boreal latitudes of the Northern Hemisphere (*1*). However, the mechanisms and the detailed spatial pattern of this Northern Hemisphere terrestrial sink remain elusive. On page 574 of this issue, Houghton *et al.* (*2*) synthesize the information on a leading candidate—historical changes in land use—for the United States. They conclude that during the 1980s, U.S. ecosystems accumulated carbon at a rate of 0.15 to 0.35 Pg/year [petagrams (10^{15} grams) per year], equivalent to about 10 to 30% of U.S. fossil fuel emissions. This conclusion is consistent with atmospheric analyses (*1*), which indicate that there is a sink for carbon of about 2 Pg/year north of approximately 30°N (*3*), although these analyses were unable to constrain the longitudinal distribution of the sink. However, it contrasts sharply with the result of Fan *et al.* (*4*), who suggest on the basis of atmospheric and oceanic data and modeling that the Northern Hemisphere carbon sink is predominantly North American, south of 51°N, with a magnitude about that of U.S. fossil fuel emissions. The apparent contrast between the conclusions of these two studies highlights the differences between and uncertainties asssociated with atmospheric "top-down" and terrestrial ecosystem "bottom-up" approaches.

From the perspective of terrestrial processes, the list of candidate mechanisms for

C. B. Field is in the Department of Plant Biology, Carnegie Institution of Washington, Stanford, CA 94305, USA. E-mail: chris@jasper.stanford.edu. I. Y. Fung is at the Center for Atmospheric Sciences, University of California, Berkeley, CA 94720, USA.



Quantifying carbon sinks. Schematic diagram of three approaches to quantifying terrestrial carbon sinks that result, at least in part, from changes in land use and land cover.

CREDIT: M. MILLER/VISUAL UNLIMITED

explaining the terrestrial sink is becoming longer but better quantified. Strictly biogeochemical mechanisms, such as increased plant growth in response to rising temperatures, atmospheric CO_2 concentrations, and nitrogen deposition, are clearly not the exclusive drivers. Elevated CO_2 concentrations and nitrogen deposition stimulate plant growth in many ecosystems (*5*). Measured responses to elevated CO_2 are generally not large enough, however, to explain the recent terrestrial sink, especially if this sink is concentrated in a small fraction of the land area (*6*). Recent experimental evidence indicates that elevated nitrogen deposition is also not likely to be a major contributor to the Northern Hemisphere carbon sink (*7*). Changes in ecosystems in response to past alterations in land management—including changes in timber harvesting, abandonment of agricultural land, and wildfire suppression—are emerging as additional explanations for the terrestrial U.S. carbon sink.

Changes in land management in the Northern Hemisphere are pervasive, with the impact of past changes often persisting for many decades. Until about 1960, cumulative carbon emissions from land-use modification were greater than those from fossil fuel combustion (*8*). Houghton *et al.* (*2*) have synthesized historical data on land use with a carbon cycle model (see the figure). According to their analysis, a substantial fraction of the current carbon sink in the Northern Hemisphere appears to be a result of past land management.

The spatial resolution of these conclusions and the attribution of the sink to distinct processes are necessarily coarse. Other independent data on terrestrial sinks can come from national forest inventories. Especially in economically developed regions, these inventories contain many thousands of samplings of nationwide forest resources, collected over several decades. These data, initially collected to quantify harvestable timber, can be analyzed to yield information about changes in forest carbon stocks (see the figure) (*9*). Data from experimental plots, especially long-term experimental plots in a range of managed and unmanaged ecosystems, are indispensable for improving carbon estimates from both land use and inventory approaches.

Atmospheric data such as the concentrations of CO_2 and O_2 are becoming increasingly useful for inferring terrestrial processes. Large-scale atmospheric measurements generally cannot distinguish between terrestrial mechanisms but rather allow estimates of the overall fluxes of the atmospheric compounds with limited spatial resolution (see the figure). The global network of monitoring stations provides reasonable resolution for interpretation of large latitudinal zones. Quantifying continental sources and sinks is much more technically challenging, a consequence of the small longitudinal gradients, the sparse monitoring network, and the limited capabilities of current atmospheric models. Fan *et al.*'s error analysis (*4*) clearly reveals this limit. Their central estimate assigns about 75% of the Northern Hemisphere sink to North America, but one standard deviation around this mean includes both 100% of the sink in North America and a 50-50 balance between North America and Eurasia. An increase in the number and accuracy of the stations that monitor the three-dimensional distribution of atmospheric CO_2, including vertical profiles and column totals, will be critical for assessments seeking greater spatial resolution. Accurate measurements of other atmospheric constituents, including ^{13}C, ^{14}C, O_2, and CO, will be increasingly important for interpreting measurements of CO_2 concentrations and validating hypotheses about carbon sinks.

The growing appreciation of the role of past changes in land management for terrestrial sources and sinks of carbon should stimulate a rethinking of the terrestrial carbon cycle. A substantial carbon source from forest clearing and a subsequent sink from land management have broad implications. Future research on the terrestrial sink may need to focus as sharply on the history of past management as on ecosystem responses to future changes in climate and atmospheric composition. In experimental studies on the carbon cycle, the interaction of global changes with land management should receive the same priority as the responses of natural ecosystems.

Sinks associated with recovery from past land management eventually saturate. The time until saturation is determined largely by the date at which forests started growing. In the United States, a substantial component of the current sink appears to result from long-term consequences of processes begun in the early decades of this century, which may be well on their way to saturation. This also means they are explicitly eliminated from consideration in the Kyoto Protocol as sinks for carbon offsets, because the protocol counts only deliberate actions to reforest, establish new forest, or slow deforestation since 1990.

References and Notes

1. P. P. Tans, I. Y. Fung, T. Takahashi, *Science* **247**, 1431 (1990); P. Ciais *et al.*, *ibid.* **269**, 1098 (1995); R. F. Keeling *et al.*, *Nature* **381**, 218 (1996).
2. R. A. Houghton, J. L. Hackler, K. T. Lawrence, *Science* **285**, 574 (1999).
3. The area of the United States is about 15% of the land from 30° to 70°N.
4. S. M. Fan *et al.*, *Science* **282**, 442 (1998).
5. H. A. Mooney *et al.*, in *The Terrestrial Biosphere and Global Change: Implications for Natural and Managed Ecosystems*, B. H. Walker, W. L. Steffen, J. Canadell, J. S. I. Ingram, Eds. (Cambridge Univ. Press, Cambridge, 1999), pp. 141–189.
6. M. V. Thompson, J. T. Randerson, C. M. Malmström, C. B. Field, *Global Biogeochem. Cycles* **10**, 711 (1996); P. Friedlingstein *et al.*, *Global Biogeochem. Cycles* **9**, 541 (1995).
7. K. J. Nadelhofer *et al.*, *Nature* **398**, 145 (1999).
8. R. A. Houghton *et al.*, *Ecol. Monogr.* **53**, 235 (1983); R. J. Andres, G. Marland, I. Fung, E. Matthews, *Global Biogeochem. Cycles* **10**, 419 (1996).
9. P. E. Kauppi, K. Mielikäinen, K. Kuusela, *Science* **256**, 70 (1992).