Scientists are mounting an ambitious effort to trace the flux of carbon dioxide between land and air; their success will help decide the fate of the Kyoto climate change treaty

Coming to Grips With the World's Greenhouse Gases

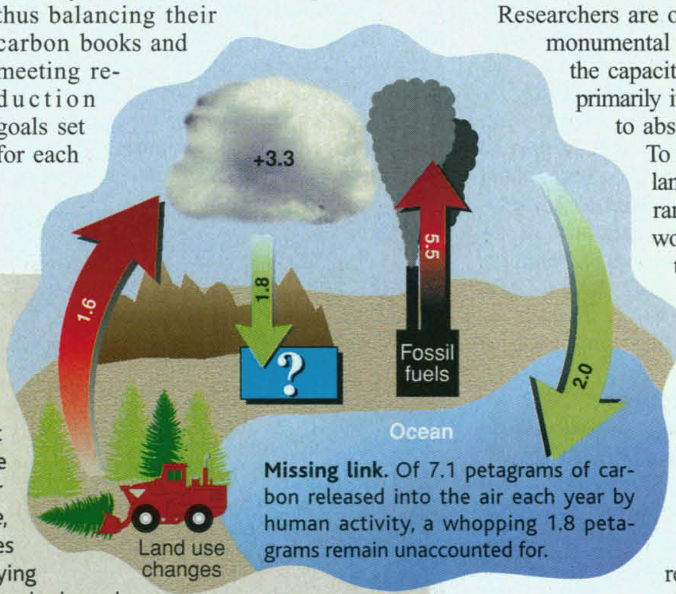
Forester Matt Delaney always dreamed of working in the tropics, so when he was asked to help measure carbon stored in 634,000 hectares of humid forest in Bolivia, he jumped at the chance. During 6 months last year, he and 10 Bolivian foresters fought their way through an area twice the size of Rhode Island to sample trees, soil, and ground cover at 625 sites. Along the way, they had to contend with relentless bees and the odd piranha attack.

"There was never anything easy about it," says Delaney, who works for Winrock International, a nonprofit in Morrilton, Arkansas. But the survival school–cum–carbon project is paying off. The team, he says, now has a good sense of how much carbon dioxide has been sucked out of the atmosphere by this primeval forest—a necessary baseline for tracking changes in carbon storage if the world were to warm in the coming decades.

Such information is not meant to fill almanacs: Scientists and policy-makers of all political persuasions perceive the world's forests as a vast sponge for CO_2 belched out by factories, cars, and other societal sources. Canny business leaders view carbon storage as a way to offset industrial CO_2 emissions, thus balancing their carbon books and meeting reduction goals set for each country under the climate change treaty that 174 nations in Kyoto, Japan, agreed to last December. Environmental groups, meanwhile, see forest preservation as a savior for staving off global warming. "Forests are one of the few ways to take CO_2 out of the atmosphere—there's no technology on the horizon to do that," says Tia Nelson, senior policy adviser at the Nature Conservancy in Washington, D.C.

Researchers are only now grasping the monumental task of understanding the capacity of Earth's surface—primarily its oceans and forests—to absorb greenhouse gases. To track CO_2 flux between land and air, scientists are ramping up a global network of monitoring stations; their data could help in assessing whether nations are adhering to the Kyoto treaty (see p. 506). And, in 2 years, engineers will undertake a novel pilot project to pump CO_2 into the Pacific Ocean as a possible way to reduce atmospheric gas concentrations (see sidebar on p. 505). But no scientific issue is thornier than gauging how much CO_2 can be socked away in forests.

Negotiators hammering out the details for implementing the Kyoto accord have agreed that changes in forest cover since 1990 can be counted for—and against—a nation trying to meet its CO_2 emissions obligations. But the treaty is hazy about how to calculate forest carbon stocks and whether nations can use forestry projects in developing countries to claim carbon credits. Efforts to clarify the CO_2-forest connection have just begun in earnest, with a U.N. workshop scheduled for September, and the results will be critical to the treaty's success. "If policy-makers are not well informed about the carbon cycle," says Michael Apps of the Canadian Forest Service in Edmonton, Alberta, "they will fail to meet the [treaty's] objective of stabilizing greenhouse gas concentrations in the atmosphere."



Missing link. Of 7.1 petagrams of carbon released into the air each year by human activity, a whopping 1.8 petagrams remain unaccounted for.

SOURCE: WOODS HOLE RESEARCH CENTER

Closing the Carbon Circle

The Kyoto treaty has begun to reshape the efforts of thousands of climate change scientists around the world. The treaty's spotlight on the carbon cycle is already helping to drive a major overhaul of the multibillion-dollar U.S. Global Change Research Program (*Science*, 12 June, p. 1682). This week's lead Focus stories explore the major scientific uncertainty underlying the Kyoto treaty—how much carbon is stored and released by the world's forests (see this page)—and how a global monitoring system will track carbon dioxide flux between land and air (see p. 506).

Bedeviling negotiators attempting to implement the treaty is a huge mass of carbon, some 1.8 petagrams (10^{12} kilograms), released into the air each year that currently cannot be accounted for in known land and sea carbon sinks (see above). "We see uptake but nowhere near big enough," says land-use expert Richard Houghton of the Woods Hole Research Center. Scientists have four main approaches for ferreting out this missing carbon: sampling CO_2 levels in the air, measuring carbon in forests and analyzing human-altered landscapes, erecting towers that trace CO_2 flux between land and air, and using satellites to estimate photosynthesis—and thus CO_2 consumption by plants—across ecosystems. The treaty has made it more important than ever to pursue all these approaches, climate researchers recently argued in *Science* (29 May, p. 1393). Says National Oceanic and Atmospheric Administration ecologist Dennis Baldocchi, "I'm in favor of mixing all four models, almost like the blind men and the elephant"—but hopefully with greater success.

At a meeting of the treaty parties in Bonn last month, the Intergovernmental Panel on Climate Change (IPCC) was asked to prepare a report due out in mid-2000 on the key uncertainty—the role of forests in the carbon cycle. "Our job is to say what can possibly be done and how we can ensure compliance with the protocol," says IPCC chief Robert Watson. Solving these uncertainties is a huge task. However, Watson says, "the only thing that matters at the end of the day is what the concentrations of greenhouse gases are."

—JOCELYN KAISER AND KAREN SCHMIDT

A Way to Make CO_2 Go Away: Deep-Six It

While climate experts try to get a better fix on the carbon cycle, some engineers are taking what they view as the obvious next step: devising schemes for funneling excess CO_2 into the deep ocean, unminable coal seams, abandoned oil fields, and isolated aquifers. One idea now leading the pack is to pipe CO_2 waste from power plants to the bottom of the sea.

The notion is not as farfetched as it may sound. In a project that has won support from some environmentalists, the Norwegian oil company Statoil since August 1996 has shunted 1 million tons per year for the last 2 years of CO_2, a byproduct of natural gas production, into a salt aquifer in the North Sea—CO_2 that otherwise would have added 3% to Norway's carbon emissions. The CO_2 should eventually form a bubble under the formation's shale roof.

Because there aren't enough aquifers in convenient places to hold all the world's extra CO_2, scientists are gearing up to test another approach on a pilot scale in the Pacific Ocean. Last December, the U.S., Japanese and Norwegian governments agreed to launch a $4 million experiment off Hawaii's Kona Coast in the summer of 2000. Engineers will extend a 2- to 3-kilometer pipe down a steep slope, so that it reaches about 1000 meters below the ocean surface. Liquid CO_2 sprayed out of a nozzle will mix with seawater and be swept away by deep currents. Scientists will follow the fate of the CO_2—300 tons over 30 days—with sea-floor instruments and from remote vehicles.

About 90% of the CO_2 produced on Earth already gets sucked up by oceans eventually, so, in a way, "we're trying to help nature along here," says Massachusetts Institute of Technology chemical engineer Howard Herzog.

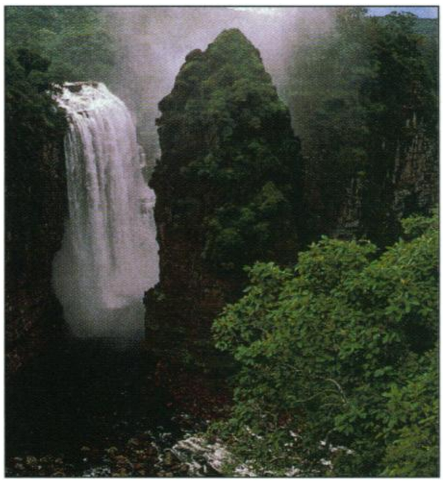
But major uncertainties loom over this approach, says Ben Matthews, a chemical oceanographer at the University of East Anglia in the United Kingdom. For example, he notes, solid hydrates formed from CO_2 and water could clog the pipe, and CO_2-laced water—more acidic than normal seawater—could harm marine life. CO_2 could also resurface if bottom currents, which ought to circulate the CO_2 for centuries, were to shift. Another contentious issue is that preparing CO_2 from power plants—scrubbing off impurities and pressurizing the gas—could require up to 30% of the energy that produced the original CO_2. Until the experiment is done, says Perry Bergman of the Energy Department's Federal Energy Technology Center, "no one is ever going to know whether it makes any sense or not." **–J.K.**

Seeing the forest for the trees

The Kyoto agreement requires 38 nations to come up with a baseline assessment for 1990 of their greenhouse gas emissions from all sources—including changes in land use—and of their carbon stocks. Then, they must reduce emissions by an average amount (7% for the United States) during the years 2008 to 2012. These targets will be adjusted for "verifiable changes in carbon stocks" because of "direct human-induced activities of afforestation, reforestation and deforestation since January 1, 1990." In broad terms, researchers estimate that deforestation currently results in about 20% of CO_2 emissions worldwide, and that afforestation—planting new forests—and reforestation draw CO_2 from the atmosphere. But those generalizations provide a shaky basis for binding, international commitments that have huge economic consequences.

One big problem is that scientists are now 8 years late—and counting—in setting the 1990 baseline. "I'm not aware of any country that has a scientifically rigorous inventory for forests in 1990," says Darren Goetze, a biophysicist at the Union of Concerned Scientists. Even for the United States, he says, a national picture of forest density was compiled from satellite data only 5 years ago—a picture that's still being filled out by ground measurements. This uncertainty, says Dan Lashof, a senior scientist at the Natural Resources Defense Council, could result in countries being rewarded for savings that simply result from more accurate field data. "This could undermine any significance of the Kyoto protocol," he says. What's needed to plug the gaps in knowledge about carbon sequestration in forests, Lashof says, is a comprehensive system for monitoring carbon stocks that combines remote sensing with ground-based sampling—including a global effort to track CO_2 (see next page)—and which provides consistent data from country to country.

The $10 million project in Bolivia is one of the largest attempts to replace the generalizations with real numbers for a specific tropical forest. The Noel Kempff Climate Action Project, as it is called, came about in 1997 when an unlikely coalition of The Nature Conservancy, the Bolivian government, a Bolivian foundation called Friends of Nature, and three U.S. companies (American Electric Power, British Petroleum America, and PacifiCorp) bought logging rights and began training local people on how to protect and use the forest—for example, by harvesting hearts of palm and breeding orchids instead of clearing the land to grow corn. The project is guided by mounting evidence that carefully managed forests can soak up CO_2 (*Science*, 18 July 1997, p. 315).



HERMES JUSTINIANO

Carbon windfall? Project hopes to get credit for keeping CO_2 in this Bolivian rain forest.

Data gathered last year suggest that this forest swath sequesters about 15 million metric tons of carbon that would have been released over the next 3 decades if timber companies, farmers, and other developers were allowed to deforest the land. To arrive at that figure, the team first had to measure carbon in the forest's trees, leaf litter, ground cover, and soil. Next, they estimated how much carbon would have been lost to development. To do that, they sampled nearby farm fields—carbon paupers compared to mature forest—to project how much CO_2 would be released if 13,000 hectares of forest were razed for cropland, and they estimated how much carbon would have been lost to proposed logging. By both stemming carbon loss and perhaps allowing the sink to continue accumulating, the coalition hopes to use the predicted carbon savings as "credits" to meet targets for reducing their CO_2 emissions.

But it is far from certain the strategy will work. Any benefits could be erased if conserving forest carbon in one place simply shifts deforestation elsewhere. Such concerns were on the table in Kyoto, where negotiators hotly debated whether to give credits and debits for forest alterations at all. Many parties believed that "by allowing forest sinks to be counted, it's almost like giving permission to extract more fossil fuels and do more oil exploration," says Jennifer Morgan, climate policy officer at the World Wildlife Fund. Because forest carbon stocks could be a deciding factor in whether a country meets its emissions target, she says, "we ought to be very cautious" about how this part of the treaty is implemented.

A matter of definition

World Bank environmental chief Robert Watson, chair of the United Nations' Intergovernmental Panel on Climate Change, agrees on the need for caution. To make the treaty work, he says, nations must adopt environmentally sound definitions of forest alterations—an unclear definition could backfire. For example, if "deforestation" leaves out destruction from fire, and "reforestation" is defined as planting trees where forest used to grow naturally, then some countries might encourage burning down forests and replanting them later for credit. This would result in a net carbon loss to the atmosphere because the new forest could take decades to store as much carbon as the original forest. Scientists will discuss possible definitions at the September workshop.

Experts agree that those definitions and the calculations for determining whether countries meet the Kyoto goals must take into account different forest types. "If you have a forest like part of the Brazilian Amazon that regrows slowly ... and is inefficient to harvest and use, then it may be best to leave it protected," says Gregg Marland of the Oak Ridge National Laboratory in Tennessee. But for fast-growing forests that can be harvested easily, such as in the southeastern United States, he says, "then it's best to make forest products" that sequester carbon or displace other carbon-intensive materials such as cement.

The global picture may seem overwhelming, but sequestration efforts such as the Noel Kempff project in Bolivia suggest that it is possible to take steps now. Whether such schemes will count under the treaty is expected to be a hot topic at a treaty meeting in Buenos Aires in November, in part because most Latin American countries—which already have forest conservation programs they want to bolster—are lobbying for it. But Nelson of the Nature Conservancy predicts the issue will not be resolved soon: "Working out how to do these projects is very complicated, because there's so much room for interpretation, so many agendas, and so much at stake."

–KAREN SCHMIDT

Karen Schmidt is a writer in Washington, D.C.

CLIMATE CHANGE

New Network Aims to Take the World's CO_2 Pulse

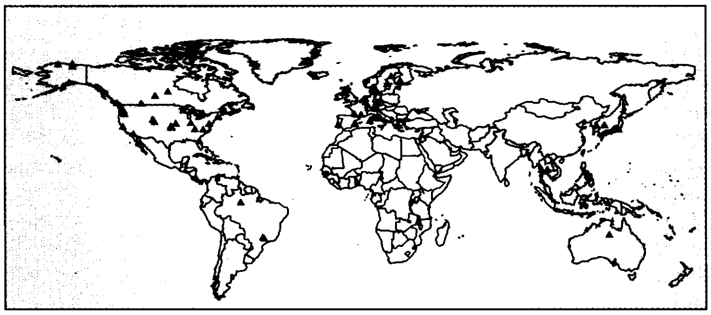
An expanding array of carbon dioxide monitoring towers around the world could help scientists pin down carbon sinks and enforce the Kyoto Treaty

This spring, a gleaming, 50-meter aluminum tower rose among the aspens and red maples in a Michigan forest, "almost like an extra tree," says Jim Teeri, director of the University of Michigan Biological Station near Pellston. Towers also sprouted in a California grassland, a Quebec wetland, and a Costa Rican rainforest. Fitted with devices for sensing faint whiffs of carbon dioxide, the towers are the latest tool for answering a key question in climate change models: how much carbon is sequestered by ecosystems.

Until now, researchers have picked at the edges of the carbon-cycle problem, either modeling fluxes globally or looking at tree growth and other clues to carbon storage. But a worldwide network of 70 or so towers now running or about to come online will soon churn out a stream of data on how much CO_2 is socked away in various soil and plant types. That information should, over the long haul, help refine models of global warming as greenhouse gases continue to build up in the atmosphere. "To see what the terrestrial biosphere is going to do in the future, data from these sites are crucial," says Dave Hollinger, a U.S. Forest Service ecologist.

The need for such data has become more pressing now that 38 nations have pledged to slash carbon emissions under the Kyoto treaty. Tracking CO_2 flux between land and air is "enormously important for what becomes of the treaty," says NASA ecologist Tony Janetos. Indeed, notes Riccardo Valentini of the University of Tuscia in Italy, a flux tower network "can be an independent way to verify [the cuts] that the Kyoto protocol requires." Others caution that the science of tracking CO_2 is still in its infancy. "It seems like a promising approach," says ecologist and climate modeler David Schimel of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, "but it's also exploratory."

The towers will help probe a long-standing mystery: the so-called "missing carbon." Only half the 7.1 petagrams of carbon released by fossil fuel burning and biomass destruction each year stays in the atmosphere. The ocean absorbs 2 petagrams, leaving unaccounted for a whopping 1.8 petagrams—enough carbon to fill a soccer field with a pile of coal 230 kilometers high (see diagram on p. 504). When scientists feed data on atmospheric CO_2 levels collected worldwide into climate models and subtract fossil fuel emissions, the results point toward the Northern Hemisphere as a major carbon sink. But forest inventories and land-use studies fail to explain where all the carbon goes, says Schimel, perhaps because these approaches do not fully account for soils, which may absorb as much as two-thirds of the missing carbon.



Spotty coverage. The global Fluxnet project will feature towers tracking the movement of carbon dioxide between various ecosystems and the air.

SOURCE: OAK RIDGE NATIONAL LABORATORY

The towers will track carbon by measuring CO_2 breathed in and exhaled by plants and soils. The technique, pioneered in the 1970s, uses wind velocity sensors and infrared gas analyzers to measure CO_2 in air drafts. But "lots of funny things can happen," says Harvard University atmospheric chemist Steven Wofsy. For example, weak nighttime drafts and other factors can lead to underestimates of CO_2 release by 10% or more. Despite this drawback, Wofsy's team has shown that warm temperatures alone do not spur carbon storage at the Harvard Forest—abetting factors include a long growing season, cloud-free summer days, and less snow cover (*Science*, 15 March 1996, p. 1576). And a study in Canada found that as Earth warms, boreal ecosystems may turn into major sources of CO_2 from thawing peat (*Science*, 9 January, p. 214).

Eager to find out what the towers might reveal about other biomes, researchers running 24 North American flux towers are now organizing a long-term network, called Ameriflux, to monitor ecosystems as diverse as tundra, cropland, and old-growth forest. The towers will measure CO_2 about 10 times a second over the next 3 years. The Ameriflux team is also linking up with a 3-year-old network in European forests and other towers in Japan, the Amazon, Australia, Siberia, and Southeast Asia. Called Fluxnet, the data-sharing project is funded by NASA, which wants to use the data to calibrate an Earth Observing Satellite (slated for launch next