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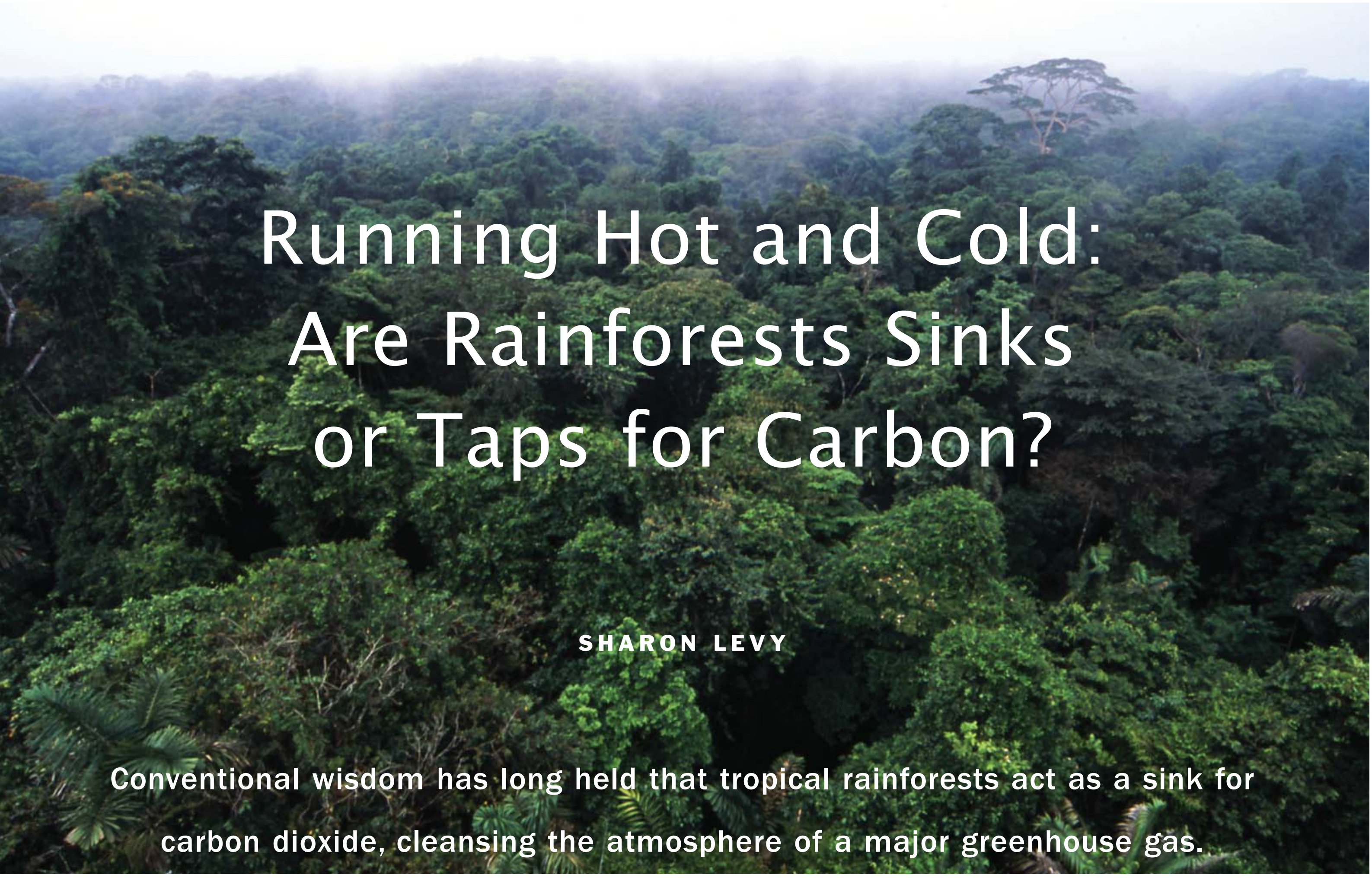

Running Hot and Cold: Are Rainforests Sinks or Taps for Carbon?

SHARON LEVY

Conventional wisdom has long held that tropical rainforests act as a sink for carbon dioxide, cleansing the atmosphere of a major greenhouse gas. However, biologists studying the forests of Costa Rica are finding that rising temperatures are causing trees to grow less and to pump out more carbon dioxide, adding to an accelerating pattern of global warming.

Below me, toucans and green macaws squawk, now and then bursting out of the foliage to show their splendid colors. A half-kilometer away, the topmost branches of a tall tree wave in the still air as a troop of white-faced capuchin monkeys moves through the canopy. I stand at the top of a 42-meter-tall research tower that sprouts out of the old-growth rainforest at La Selva Biological Research Station, in northeastern Costa Rica. On a clear day, I'd have a view of the chain of volcanoes to the west and the bright blue of the Caribbean to the east.

But on this March morning, rain drizzles onto the forest canopy, which surrounds the tower in a rolling panorama of every possible shade of green, then fades into a cloak of low-lying clouds. Up here, where scientists are measuring the exchange of greenhouse gases between the dense trees and the planet's troubled atmosphere, the forest seems to go on forever. In fact, La Selva is only a small haven of surviving rainforest, 1614 hectares surrounded by farmland and other kinds of development. Deborah Clark, who along with her husband and fellow ecologist David Clark has devoted a long career to studying La Selva's

On a cloudy day, the rainforest seen from the top of the La Selva canopy research tower seems to go on forever. In fact, La Selva is the small tip of a peninsula of remnant habitat in a landscape heavily altered by human activities. Some researchers believe this may make data from La Selva less relevant to conditions in Amazonia and other areas with large swaths of tropical forest. Photograph: © 2001 Greg and Mary Beth Dimijian.

complex inner workings, describes it as a "postage stamp" of intact habitat in a landscape heavily altered by the hand of man.

Despite its small size, this forest is having a big impact on the shifting science of climate change and tropical ecology. The Clarks, who started out more than 20 years ago intending to study the basics of tree growth and physiology, have followed their data into an intense debate over the future of tropical forests in a warming world. What they've discovered both fascinates and dismays them.

"When we started out in the early 1980s," explains Clark, "we chose six ecologically different kinds of trees that grow into the canopy. We wanted to figure out, from being babies all the way to becoming old senescent adults, how trees survive, to understand how we can have so many species coexisting." More than 350 different types of trees make up La Selva's forest, which is populated with a spectacular diversity of creatures, including peccaries, agoutis, three kinds of monkeys, and many hundreds of species of birds, bats, and ants. To begin to uncover the secrets of this rich ecosystem, the Clarks and their crew began by simply measuring the diameters of selected trees over and over, year by year. More than a decade into the project, some startling results jumped out at them.

Ecologists had assumed that trees in the consistently warm tropics grew at a slow but steady rate, unvarying from one year to the next. But the trees at La Selva grew less in hotter years, more in cooler ones. Over 16 years of sampling, from 1984 to 2000, dramatic differences in growth rate occurred: In some cooler years the trees added twice as much wood as they did in the scorching El Niño year of 1997–1998. All six species of trees, representatives of divergent plant families with different life histories, showed the same pattern.

Workers set up a portable 46-meter-tall research tower in the rainforest at La Selva Biological Station, Costa Rica. At 71 different sites scattered throughout the reserve, towers like this one were erected, allowing researchers to sample biomass from the muddy earth to the top of the forest canopy. The work is part of the Carbono project, an innovative effort to measure carbon flux throughout the entire ecosystem. Photograph: Mike G. Ryan.

First hints of carbon efflux

Tree growth is an index of the balance between photosynthesis, in which plants fix carbon and release oxygen, and respiration, in which plants use up oxygen and breathe out carbon dioxide. Global temperatures are now rising fast, driven by human emissions of carbon dioxide and other greenhouse gases. The data from La Selva were among the first hints that tropical forests might be pushed by increasing heat to release more carbon dioxide, intensifying global warming. This suggested a reversal of the popular theory that tropical forests act as a sponge, soaking up much of the excess carbon dioxide humans pump into the air.

While grappling with their new findings, the Clarks discovered that their data are consistent with a model of global carbon flux developed by Charles David Keeling, a pioneering chemist with the Scripps Institution. In the 1960s, Keeling, who died in 2005, demonstrated that atmospheric levels of carbon dioxide were steadily rising as a result of human activities. (The two major anthropogenic sources of atmospheric carbon dioxide are combustion of fossil fuels and destruction of tropical forests.) He and his colleagues built their model on measurements of carbon dioxide concentration, taken throughout the 1980s and 1990s at nine stations scattered from the Arctic to the Antarctic, and on estimates of worldwide fossil fuel emissions and prevailing winds.

From this model, Keeling concluded that the amount of carbon dioxide taken up in tropical landmasses peaked in cool years and fell in hotter ones, accounting for year-to-year changes in the amount of human-generated carbon dioxide that stayed in the atmosphere. "The amazing thing," says Clark, "is that the Keeling model, based on global atmospheric gas sampling, is perfectly correlated with our tree growth record here at La Selva. This is the first and only case of a long-term biological data set supporting one of these models. So I think the Keeling model is onto something."

Tropical forests cover a relatively small portion of the Earth's surface, but they are thought to be responsible for more than a third of plant productivity. The La Selva data suggest that trees could be very sensitive to the kinds of temperatures already hitting the tropics. It's not just a question of hypothetical effects as the climate warms; the rainforest has already been panting in the heat, most notably in the intense El Niño year of 1997–1998. A newly published study of forests in Panama and Malaysia shows a temperature-related decrease in tree growth rates that parallels the La Selva findings, and recent studies of rice fields in the tropics suggest that crop productivity drops with rising temperatures.

Steven Oberbauer, of Florida International University, is collaborating with the Clarks, supervising studies of the movement of carbon dioxide between La Selva and the sky above. Mounted on the tower that thrusts out of the center of the forest is high-tech equipment used in eddy flux analysis, in which measurements of wind speed and direction are combined with data on carbon dioxide concentration to track the flow of carbon in and out of the ecosystem. Using a measurement system designed by Hank Loescher, a forest ecologist at Oregon State University, the researchers have so far collected only a few years of data. What they've recorded supports the Clarks' findings. In cooler years, when the trees grow faster, they absorb more carbon out of the atmosphere. In hot years, they take up less carbon dioxide and breathe out more.

Research assistant Harlyn Ordóñez measures photosynthesis of canopy tree leaves with a portable photosynthesis system at the top of a sampling tower. Frequent measurements of wind speed and direction are combined with measurements of ambient carbon dioxide concentrations to track the exchange of carbon between the forest and the atmosphere. Photograph: Mike G. Ryan.

Stirring debate

Laboratory experiments established long ago that plants increase their rate of photosynthesis as temperatures rise. But at some critical temperature, they hit a physiological wall, and photosynthesis crashes. The idea that intense heat can sap a plant's productivity, says Clark, is "Ecophysiology 101." Yet when the Clarks and Keeling coauthored a paper on their matching results in *Proceedings of the National Academy of Sciences* in 2003, their analysis caused a stir.

Some researchers take exception to the Clarks' argument because it extrapolates from a small remnant of rainforest to all the forests of the tropics. Loescher points out that this forest is unique: an island of trees surrounded by farms, residences, and tourist developments. "I strongly suspect that all this land-use change makes for hotter and drier air masses that affect La Selva, contributing toward the alteration of carbon exchange and plant productivity when compared to undisturbed forests," he says. Loescher notes that the three years of eddy flux data he collected there follow the observed pattern of changing tree growth. But he believes the Clarks oversimplify when they tie the pattern only to fluctuating temperatures. In his view, drier conditions in hotter years, along with increased cloud cover in the wet season during El Niño years, contribute to the drop in plant productivity. "Just looking at temperature is fairly simple and does not have a lot of explanatory power, though the pattern is compelling."

Steven Wofsy, an atmospheric chemist at Harvard who has studied carbon exchange in the Amazon, shares some of Loescher's reservations. "The Keeling–La Selva correlation implies that La Selva is a good proxy for global tropical forests," he says. "That's plausible, but hardly proven." Wofsy's studies in the Amazon were not as long-standing as the Clarks' data set, but the pattern of change documented there did not mirror La Selva's. "When we first got there our site was losing carbon," he says, "but over the five years we were there, it turned around into a carbon sink." The trend was part of a response to past disturbance, as smaller trees shot up fast in the openings left by fallen forest giants.

Deborah Clark knows that her theory is far from ironclad. "There is the $n = 1$ problem: You should never leap off into space based on one sample," she says. "There are lots of reasons to say it would be ridiculous to extrapolate from this forest to the world tropics. Yet we've got this incredible parallel between how trees react to yearly climate variation here and what the Keeling model says the world tropics are doing. I have to think there's a big signal out there, related to rising temperatures."

The Clarks' evidence contradicts the idea that tropical forests act as a major sink for excess atmospheric carbon dioxide. Laboratory experiments had shown that increased levels of carbon dioxide could lead to impressive changes in plant growth rates: Some crops showed a 33 percent jump in productivity in response to a doubling of carbon dioxide concentrations. The Intergovernmental Panel on Climate Change (IPCC), in its 2001 report, optimistically endorsed the idea that "CO_2 fertilization" would result in forests and farmlands sucking more and more carbon out of the air.

In the late 1990s, researchers working in the tropics found evidence that forests were responding to increasing levels of atmospheric carbon dioxide with a burst of new growth. Oliver Phillips, of the University of Leeds, headed a group of researchers who reviewed long-term growth data from South American tropical forests. In a report published in *Science* in 1998, they concluded that in most of the study sites, growth exceeded losses from tree death, and that trees had packed on about one metric ton of carbon per hectare per year in recent decades, acting as a major sink for excess carbon dioxide.

Meanwhile, eddy flux studies in the Amazon, the largest intact tropical forest in the Americas, were yielding numbers that showed far more carbon dioxide was going into the ecosystem than was coming back out. Some researchers concluded that tropical forest uptake could account for all of the mysterious "missing carbon sink"—the difference between the amount of carbon dioxide pumped into the atmosphere each year by human activities and the amount that actually stays there. In some years, this sink amounts to 50 percent of total emissions.

But if Amazon forests were sucking down a ton of carbon per hectare every year, says Clark, "that forest would end up looking like the Empire State Building. Something just doesn't add up."

In November 2003, Wofsy and his colleagues published a paper in *Science* reporting the results of their eddy flux studies at Tapajos National Forest in Brazil. It was the first project to record a net loss of carbon from a forest in the Amazon. One crucial difference between this study and previous work was in the way the scientists interpreted their eddy flux data.

Wofsy explains that valid eddy flux data depend on the constant movement of air. Mounted at the top of an eddy flux tower is a sonic anemometer, a device that measures wind speed and direction 10 times every second. These numbers are linked with carbon dioxide concentrations, measured once every second. "If the air is not moving," he says, "that experiment doesn't work very well."

At night in the deep forest, air tends to become still. In the dark, photosynthesis ceases, but plants continue to breathe out carbon dioxide, a factor that can be accounted for only if researchers correct for the lack of nighttime winds. "The first long-term eddy flux study was begun by me and my group at Harvard Forest in 1989 and is still ongoing," says Wofsy. "We published results in 1993 which showed that you need to carefully correct for time periods when the atmosphere is very stable." The researchers who'd been claiming a major carbon sink in the Amazon had failed to make this correction, and so they missed much of the carbon being exhaled by the forest.

Forest succession

I follow Leo Campos and William Miranda, two Costa Rican research assistants who have been working with the Clarks for more than a decade. They move deftly through the tangled forest, working on the annual census of tree growth that has been tracked for 25 years. Here on the forest floor, life for La Selva's trees is revealed as a never-ending competition for sunlight. Seedlings no thicker than my pinky finger may be 10 or 20 years old, unable to grow much in the understory until a branch or a whole tree falls, leaving a precious gap in the solid roof of leaves. Some trees that have at last reached the canopy are more than 200 years old but surprisingly slender: I could easily wrap my arms around the trunks.

To measure growth on the bigger trees, Campos climbs a ladder to measure the girth of the trunk above the thick buttresses typical of many tropical species. These radiate out from the tree's base like spokes on a massive wheel; the width of the buttresses increases much faster than the overall biomass of a tree. Deborah Clark believes some of her colleagues overestimated tree growth in their studies because they made the mistake of measuring around buttresses.

Phillips and his colleagues were trying to do "a very cool thing," says Clark. "But they were taking any data they could find. We know for a fact that many people were measuring trees in the tropics wrong, measuring around buttresses. They're very wide and grow very fast and really have zip to tell about how the tree is doing."

In 2004, the Phillips group published a second study, in which such faulty data sets had been weeded out. Once again, they concluded that tropical forests in the Americas are a carbon sink. Based on tree growth data from 59 study plots in Amazonia, they estimate that tropical forests are taking up about 0.9 metric tons of carbon per hectare each year. Still, in a review paper in *Philosophical Transactions of the Royal Society* in February 2004, Phillips and coauthor Yadvinder Malhi emphasized that a tropical carbon sink should not be taken for granted. "There is some evidence that intact tropical forests may be increasing in biomass and acting as a moderate carbon sink.... Almost all researchers agree that this sink cannot be relied on and may even reverse in the coming century," they wrote.

"I've never believed that tropical forests were a major carbon sink," says Wofsy. That theory ignores the constant disturbances innate to tropical forests, which he's experienced firsthand. His research in Brazil ended after repeated tree falls destroyed three expensive eddy flux towers. Tropical trees, once they're free to grow in an open patch of sun, shoot up much faster than those in temperate forests, so studies that measure only tree growth might conclude that recently disturbed, regrowing patches are a net carbon sink. But since dead wood is rotting and releasing carbon on the forest floor, tracking tree growth without also tracking carbon flux in the air gives an incomplete picture. "If we had only measured

Research assistant Leo Campos measures the girth of a rainforest tree. The Clarks' controversial theory that rising temperatures slow growth in rainforest trees is based on the longest existing data set that tracks annual growth in a tropical forest. They are now in their 25th consecutive year of monitoring. Photograph: David B. Clark.

the growth of trees, and not studied net carbon exchange using eddy flux, we'd have believed our forest was a big sink for carbon, because our trees were growing like crazy—as is often true when a forest is released by having trees knocked over."

Wofsy is one of the authors of a new IPCC report on global climate change and its social and ecological impacts. "The current report does not endorse the idea of a big carbon sponge in the tropics," he says. The report does discuss some results that suggest significant carbon uptake in the tropics, averaging in the range of 0.1 to 0.2 metric tons of carbon per hectare per year. Wofsy and many of his colleagues now believe that much of the "missing carbon" is being absorbed by forests in northern latitudes—throughout North America and Eurasia, and in boreal forests that are expanding north into tundra landscapes as the climate continues to warm.

That idea is supported by remote sensing data that suggest forest biomass is expanding in the north. Another important clue comes from studies of the isotopic makeup of carbon drifting in the atmosphere. When plants take up carbon dioxide, they leave a signature in the pool of gas left behind. Plants prefer to use carbon-12, a lighter form of the atom. Where forests play a major role in carbon dioxide uptake, the heavier isotope, carbon-13, builds up in the atmosphere. On the basis of shifting carbon isotope ratios, forests in the Northern Hemisphere have been estimated to absorb more than two billion metric tons of carbon every year.

That result makes sense, says Wofsy, because virtually every temperate forest in the Northern Hemisphere has been logged or cleared for agriculture within the last two centuries. Young trees absorb carbon much faster than mature stands. But well into the process of forest succession, temperate and northern forests remain hungry for carbon.

At Harvard Forest, which is now 85 years old (the old growth was leveled by a hurricane in 1938), the rate of carbon uptake recently doubled. "That was really unexpected," says Wofsy, "but the reason became clear as we studied the changing structure of the forest. Red oak is now becoming dominant over earlier successional species like red maple. The oaks have denser wood and can grow bigger than the maples." The same kind of pattern is likely to hold in the regenerating conifer forests of the West, and mature forests in the Northern Hemisphere continue to absorb carbon much longer than climate modelers previously assumed. Remnants of

Visit these Web sites for more information:

www.fiu.edu/~carbono/

http://cdiac.ornl.gov/trends/landuse/landuse.htm

www.as.harvard.edu/chemistry/hf/

old-growth Douglas-fir forest in the Pacific Northwest—aged 500 years or more—continue to absorb carbon.

Carbon banks

At La Selva, the Clarks, Oberbauer, Loescher, and their colleagues are engaged in an ambitious project they've dubbed "Carbono," what Deborah Clark describes as the "moonshot effort" to track carbon as it flows through the intricate channels of the tropical rainforest. At each of 71 sites throughout the forest, they've erected a portable tower and used it as a platform to measure biomass in every leaf, vine, and branch from the muddy earth to the top of the canopy. But what is above ground is only the beginning.

Most of the carbon stored in tropical forests lies beneath the earth, in live roots that grow and respire, in the rich detritus of fallen leaves and wood that feed soil microbes, and locked in the soil itself. At Carbono plots scattered throughout La Selva, researchers are gathering and weighing leaf litter, photographing the growth of tree roots with underground cameras, and encapsulating bits of the forest floor to measure carbon dioxide as it flows in and out.

Edzo Veldkamp, a collaborator on the Carbono Project who is based at the University of Goettingen, Germany, looks down into one of the three-meter-deep shafts dug into the forest soil to measure belowground carbon exchange and storage. Most of the carbon stored in many tropical forests lies beneath the earth, locked in the soil itself and in living roots and decomposing detritus. Photograph courtesy of Deborah A. Clark.

Six plots also include a perfectly symmetrical, three-meter-deep, hand-dug shaft. These research pits look like outsized graves but have the pleasant aroma of a root cellar. They allow the Carbono crew to measure carbon exchange and storage deep in the ground—and there's plenty of carbon to track.

"This forest holds something like 300 to 400 tons of carbon per hectare," says Clark. "If you cut it down, you'll lose carbon to the atmosphere far faster than the trees respire it, even in the hottest El Niño year." The razing and burning of tropical forests cleared for agriculture is a major contributor to rising global carbon dioxide levels. Even if forests throughout the tropics grow less and respire more in the hot years to come, they remain an irreplaceable storage bank for carbon.

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