A husband-wife ecologist team whose 20-year study of tropical rainforests has yielded a wealth of insights now suggests that global warming could be worse than expected

An Intimate Knowledge of Trees

Pointing out certain trees one morning in the rainforest of La Selva, Costa Rica, Deborah Clark sounds like a principal who knows every kid in the elementary school. Clark notes a "teenager" with a telephone pole–sized trunk and an "old monster" canopy tree a meter across that's likely hundreds of years old. To a visitor, the jungle seems bursting with healthy growth. But lately, Clark and her husband, David Clark, have noticed something awry: In warm years, the trees are growing more slowly and more are dying. "No year is the same as any other year," she says, "but it seems to me we're getting all kinds of weirdness."

Rainforest dwellers. Deborah and David Clark live year-round at La Selva biological station in Costa Rica, where they have amassed a unique, long-term data set.

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If anyone could tease out weirdness in a seemingly thriving tropical forest, it would be the Clarks. Since they arrived at La Selva in a dugout canoe 23 years ago, this ecologist couple—who hold strongly to their views, although he is as soft-spoken as she is feisty—have made studying this forest their lives' work. Their careful observations of the demographics of more than 3000 trees have overturned "mythology" in tropical ecology, says Ariel Lugo of the U.S. Forest Service in San Juan, Puerto Rico. Research faculty members at the University of Missouri, St. Louis, the Clarks "know the [tropical] forest as well as anyone," says Richard Condit of the Smithsonian Tropical Research Institute in Panama. Their annual measurements of tree growth are the longest such data set in the world.

Now the Clarks are using these data to warn that scientists may have underestimated the rate of future global warming. In a provocative paper published online this week in the *Proceedings of the National Academy of Sciences* (*PNAS*), the Clarks and atmospheric scientists Charles D. Keeling and Stephen Piper of the Scripps Institution of Oceanography in La Jolla, California, report that in hot years, the trees at La Selva grow less—and the world's tropics emit lots of carbon dioxide (CO_2). If tropical forests globally are as sensitive to warming, the authors suggest, they could soon become a major source of the greenhouse gas CO_2 instead of a sink. That, in turn, could send global temperatures soaring much faster than anyone has estimated.

Their findings have created a stir since the Clarks began describing them at meetings 5 years ago. Lugo, like some other scientists, says it is "very daring" to try to link a single forest to atmospheric CO_2 levels across the tropics. Chris Field of the Carnegie Institution of Washington at Stanford is cautious: "It's a very intriguing and potentially very important data set." Yet the study can't be dismissed, because the Clarks have a reputation for meticulous work that has contributed to a broad swath of tropical ecology.

Tropical beginnings

When they met 37 years ago on their first day of college at the University of North Carolina, Chapel Hill, the Clarks did not expect to spend their lives in a rainforest. Married in 1970, they became "academic clones," they say, heading off in a Volkswagen bus for graduate studies in zoology at the University of Wisconsin, Madison.

Soon after finishing their doctoral work on introduced black rats overrunning the Galápagos Islands, they answered an ad in *Science* for the first scientific director for La Selva, a small biological station run by the Organization for Tropical Studies (OTS), a university consortium. With no money to visit, they could only guess at what life would be like in a forest that gets 4 meters of rain a year. "Hot, wet, and buggy," David accurately predicted. They took the job, splitting the $12,000 salary.

Their impression on disembarking from the canoe in January 1980 was shock. The station consisted of a "ramshackle" cluster of buildings strung with naked, spliced wires, David recalls. Head-high partitions separated sleeping rooms for the mostly male researchers. "It was like moving into a tropical version of Animal House," Deborah says.

With simple ideas, the Clarks helped OTS build La Selva's research infrastructure. They got money from the U.S. National Science Foundation (NSF) to build a 5-kilometer concrete path so scientists didn't have to slog through mud. They installed posts every 100 meters across the forest that help researchers calculate their coordinates, creating a grid that remains invaluable because Global Positioning System signals can't penetrate the forest canopy. "The Clarks were absolutely essential" to making La Selva one of the world's top tropical forest research and education sites, says botanist Donald Stone, a longtime OTS director and professor emeritus at Duke University in Durham, North Carolina.

The Clarks focused their research on the demographics of La Selva's more than 300 tree species, only three of which had been studied in detail. To follow their life cycles, in 1983 the Clarks marked and mapped trees of six species. "It seemed easy to do," says David. They later added more trees and species. Twenty years later, this study keeps two technicians busy 6 months of the year, climbing ladders with tape measures and kneeling with rulers to measure 2200 trees. (Some other tropical sites have longer data sets but measure trees only every 5 to 10 years.)

Life of a tree

Before long, La Selva tree data began to yield new insights into forest dynamics. In one early paper, the Clarks confirmed the Janzen-Connell hypothesis that predicts more seedlings will survive further from the parent tree, where they are less likely to be eaten or contract disease. A 1992 paper in *Ecological Monographs* challenged a theory that tropical tree species are largely equivalent in life history, notes Richard Kobe of Michigan State University in East Lansing.

Other findings were serendipitous. For example, David decided to survey the soil of La Selva, mapping the type—alluvial or volcanic—and landscape—flat or sloped. NSF gave the project "modest reviews" because it was not hypothesis-driven, David says. But the study produced "among the strongest" evidence that canopy tree species vary along soil gradients, says Kobe.

In another influential paper in *Ecology* in 2001, the Clarks for the first time analyzed long-term tree growth from 50-centimeter-high seedlings to 50-meter canopy trees. Most surprising, they found that what they call "splatted" trees are typical: Most young rainforest trees get broken or flattened by falling debris several times before they make it to the top. These findings have "informed the whole knowledge of forest dynamics," says Robin Chazdon of the University of Connecticut, Storrs.

The Clarks produced these papers while "basically running a hotel for scientists," notes Stone. In 1994, they stepped down as directors to do full-time research. With numerous collaborators and funding sources, they started a study called Carbono—18 plots, 50 by 100 meters each—to measure the carbon stored and released by the entire ecosystem, including both trees and soil. The project includes a 42-meter tower that measures CO_2 wafting in and out of the forest, part of a worldwide network of "flux" towers.

Colleagues say the Clarks' year-round presence at La Selva contributes enormously to the quality of their data. It also gives them time for reflection. "They don't do any research without debating it back and forth for days," notes collaborator Steven Oberbauer of Florida International University in Miami. But living on site full-time does make for a bare-bones existence: The Clarks' living space consists of a screened-in bedroom and two air-conditioned offices. For excitement, they escape to an apartment in San José stocked with videos and DVDs.

Debating team

Nine years ago, the two decided to pursue separate research questions. David's focus has been ground-truthing remote sensing images using La Selva's forest. He and interns painstakingly mapped the positions of canopy trees, for instance, providing key validation—once the first satellite images came in—that the technology could discern individual trees.

Deborah became embroiled in the often intense debate over whether tropical forests are a sink for carbon. Trees soak up CO_2 through photosynthesis, but they also continuously respire CO_2. A decade ago, most climate scientists believed that these processes balanced out. But a 1995 paper in *Science* based on data from a CO_2 flux tower in the Amazon suggested that tropical forests are now absorbing carbon, perhaps because extra CO_2 from human activities acts as a fertilizer. And in a 1998 *Science* paper, Oliver Phillips of the University of Leeds, U.K., and coauthors analyzed global inventory data and concluded that old-growth tropical forests are absorbing carbon —suggesting a major role for tropical forests in slowing greenhouse warming (*Science*, 16 October 1998, p. 439).

Streeeetch. A technician measures a tree's diameter as part of a demographic study of trees at La Selva.

The *Science* paper looked dubious to Deborah, however, who noted that at some sites researchers measured trees around their buttresses, which grow faster than the rest of the tree. This could inflate biomass estimates. In an exchange last year in *Ecological Applications*, she argued that when the faulty data were excluded, the sink disappeared. Phillips's team responded that dying trees would cancel out any overestimates of tree growth. "The community views the issue as open," says ecologist David Schimel of the National Center for Atmospheric Research in Boulder, Colorado.

The Clarks have taken on even more controversy with their *PNAS* paper, which argues that rather than putting the brakes on global warming, tropical forests could hasten it. The research began when they noticed that in the warm El Niño years of 1987 to 1988 and 1997 to 1998, La Selva trees grew much more slowly. Looking across 16 years of data, they saw a pattern of decline in tree growth with warmer night temperatures, which, they hypothesize, cause trees to release more CO_2 through respiration. Meanwhile, Keeling had been charting annual variations in atmospheric global CO_2. Reading one of his papers, Deborah was struck by a "remarkable" correspondence in years when CO_2 levels rose more than usual and La Selva's tree growth slowed. She suggested a collaboration.

When Keeling focused on the tropics, he again found that CO_2 fluctuations matched annual tree growth at La Selva. Together, the authors argue, the data suggest that less growth, combined with fires, deforestation, and other processes, is making tropical forests a source of CO_2 in warmer years. During the last El Niño, they say, tropical forests pumped out a whopping 6.7 petagrams of carbon a year, an amount equal to CO_2 from worldwide industrial sources.

The Clarks' link between slower tree growth and warmer temperatures "is fascinating," says Schimel, and "extremely valuable in showing how sensitive systems might be" to global warming. But the paper ran into problems in review at *Nature* and *Science*, the Clarks say, because it attempts to link this pattern to Keeling's estimates of tropical CO_2 fluxes—and those fluxes are much higher than the ones other experts have calculated. Schimel, for one, says it's too soon to say tropical forests are already a source. And Condit questions whether tropical forests worldwide grow more slowly in warm years: "It isn't what we see in Panama," he says.

Undaunted, the Clarks are moving on to new projects, analyzing more weirdness in their Carbono plots. Not only do trees grow more slowly in warm years, but a surprisingly high fraction die. "That transition period when they're dying will put a whole lot more carbon in the air," Deborah says, especially if hardier trees don't fill the gap.

The Clarks, now 55, will probably be at La Selva "till we die," says David. "At some point, we'll start looking for academic children" to take over their research—adds Deborah—"if the trees are still around."

–JOCELYN KAISER

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