Climate Change and the Forest

Warming breeds drought, drought breeds fires,
fires release carbon, carbon breeds warming.

BY DANIEL NEPSTAD

IN 1984, ON THE OUTSKIRTS OF PAR-agominas, a bustling and violent cattle town in the eastern Amazon, I walked through a pasture, brown and dusty from drought, into a 500-acre island of virgin forest. The moist greenness of the leaf canopy that reached more than 100 feet above my head and the squishy dampness of the humus, dead leaves, and branches on the ground were a world apart from the parched African grasses and gaunt white zebu cows I had just seen. Although I didn't realize it at the time, it is in understanding the differences between these two worlds—the rainforest and the cattle pastures that are replacing them—that we begin to realize how the lives of people around the world are tied to the fate of Amazon forests. The climate of the Amazon and the climate of the planet are both dependent upon the deeply rooting, drought-resistant trees that comprise Amazon forests, just as the survival of these trees depends upon climate. The risk is that the early symptoms of climate change will act synergistically with logging, fire, and drought to replace much of Amazon rainforests with fire-prone scrub vegetation, accelerating global warming in the process.

To penetrate the complex web of relationships between climate and rainforest, we must begin with a lesson in tree physiology. Hug a tree on a warm, sunny day, and your arms surround thousands of tiny, little tubes full of water that is racing silently skyward, like soda up a straw. Everyone has seen these tubes, which biologists call "vessels" and "tracheids." They help form the grain in wood. Seasonal variations in the diameters of these tubes make up the growth rings we see on the cut surfaces of tree trunks. Wood is the plant world's most successful invention for accomplish-

ing two extraordinarily difficult tasks. Its remarkable strength allows trees to position their leaves to capture sunlight far above the ground. And its exquisite plumbing network of vessels and tracheids supplies these leaves with water absorbed from the soil.

For many years it was assumed that Amazon trees are not very good at absorbing water from the soil because of their very shallow root systems. Back in 1984, as I returned to that 500-acre forest island nearly every day of the five-month dry season, the mismatch between the assumption and what I was seeing slowly sank into my graduate-student mind. Some simple calculations led me to predict that the towering, green trees had to be absorbing moisture from at least 25 feet beneath the ground surface,
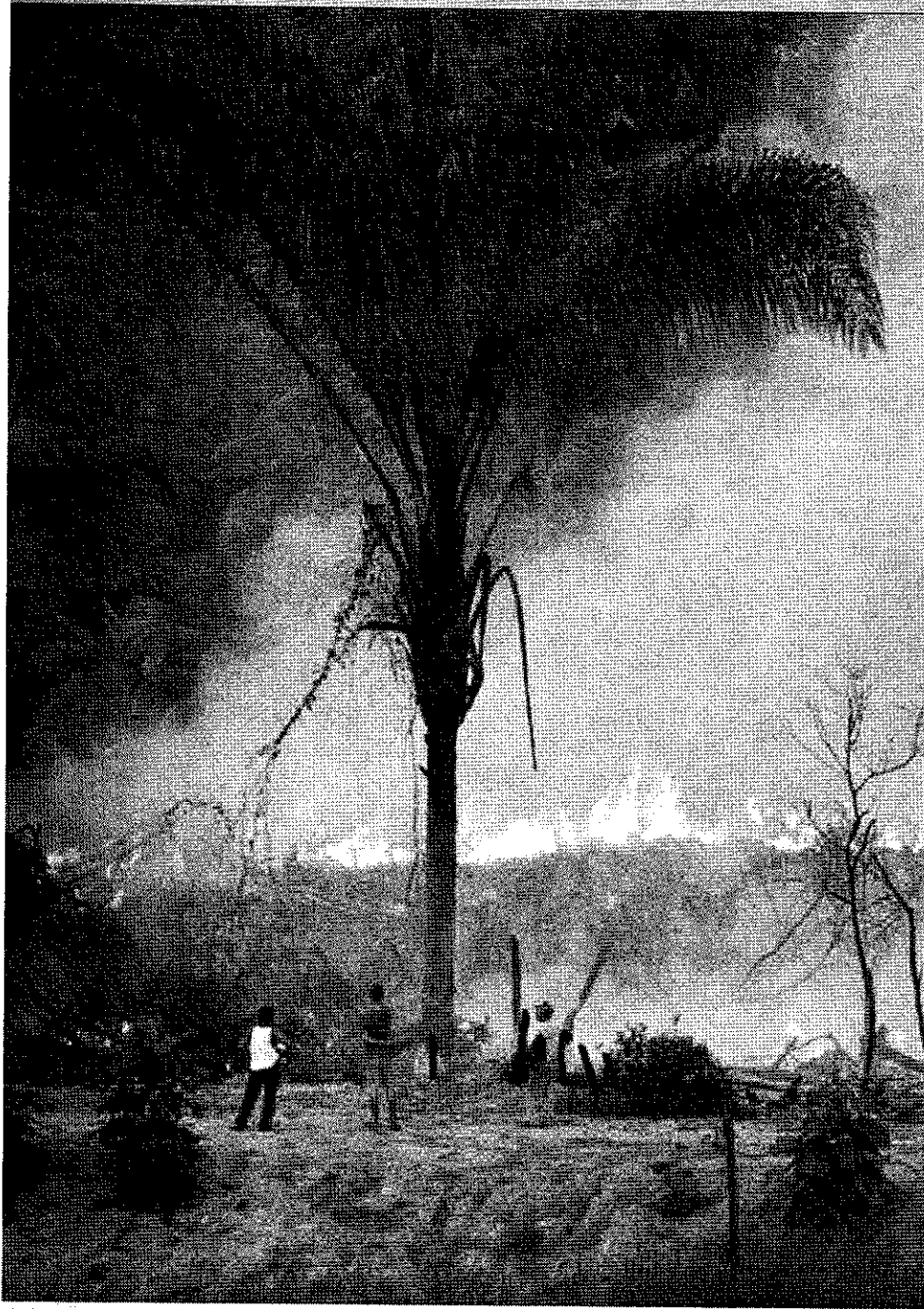
well beyond the two- or three-foot rooting depth assumed by most. Otherwise these trees would have turned brown and gone dormant, just like the African forage grasses planted in the neighboring pasture. Twenty-five feet was the depth of soil needed to store the amount of water that the forest was releasing to the atmosphere through "transpiration"—the evaporation of water from leaves into the air—and that was not being supplied by the meager, dry-season rains that had fallen. I hired some well-diggers from Paragominas, a town south of Belém, to test my calculations and look for deep roots. One hearty digger dug down 68 feet, aided by an industrial fan that pumped fresh air into his damp, dark,

grave-sized hole. The last tree roots disappeared 60 feet beneath the ground's surface. By 1992 my research team had dug dozens of deep holes across the Amazon with similar results. The assumption of shallow rooting in Amazon trees was put to rest in 1994 as we published our results in the journal *Nature* despite stiff resistance from some reviewers of our controversial findings.

Deep roots are far more than a botanical curiosity. For by allowing Amazon forests to remain green and lush during the severe seasonal droughts that affect about half of the Amazon region each year, these cryptic tree organs facilitate the release of enormous amounts of water to the atmosphere through transpiration. Thanks to deep roots, Amazon trees can supply the atmosphere with vapor year round, and this vapor is the most important ingredient of rain clouds in this region. The year-round greenness of Amazon forests is important for another reason. Fires that are lit by cattle ranchers to kill the woody brush that invades their pastures often escape from control, and burn right up to the edge of the neighboring forest. Usually the fire goes out as it encounters the damp leaves

The carbon stored in the Amazon's trees equals roughly 15 years of human-induced carbon emissions into the atmosphere.

and branches lying on the forest floor. But in 1984, ecologists Christopher Uhl and Robert Buschbacher made a disturbing discovery, also in the Paragominas region. The burgeoning logging industry of Paragominas was creating ragged holes in the rainforest, damaging 20 trees for every choice timber tree that it harvested. Uhl and Buschbacher went to forest after forest and the result was the same. The holes created by the logging teams were allowing sunlight to stream into the forest interior, drying up the damp humus and dead leaves, turning the forest floor into kindling. In the wake of logging crews, forests were losing their resistance to fire—and were burning.

In 1992 I got my first frightening

The Forest Felled: Amazonia's fires add carbon to the atmosphere and make the planet hotter.

becoming an enormous tinderbox? Would trees have died? Which ones? I realized that I couldn't wait for the next El Niño episode to find out, and I had my field crew start to build a small roof in the forest to divert rainfall from the soil. Satisfied that we could simulate a truly severe El Niño episode to learn how the forest reacts to a depletion of soil moisture, I began to raise money to expand the little soil shelter to 2.5 acres. In 1997, as forty laborers dug trenches, built towers up into the forest leaf canopy, and constructed 6,000 clear plastic panels to divert water from the soil, Peruvian coastal waters began to heat up again. For the first time, small fires that I set on the forest floor had to be put out. The humus and dead leaves had dried enough to catch fire, even without the help of logging crews. By the end of the 1997 dry season, the 500-acre forest I knew so well was gradually slipping over the edge. As our research team looked at the rainfall data from the region, we realized that this was not a local phenomenon. The forests of the eastern Amazon were being pushed to the limit of their drought tolerance. It was an environmental crisis in the making.

Our news release to the Brazilian media met with denial. Government officials declared that "the Amazon forest does not catch fire" even as the low (shin-high) naturally occurring fires burned for weeks into virgin rainforest, invisible to the official satellite-based fire-detection system. But the denial quickly melted away in January of 1998, as forest fires moved across the Brazilian state of Roraima and the homeland of the Yanomami Indians. The fires became an international emergency as images of indigenous families driven from their forest homes ran on prime-time television. The Brazilian government requested a $15 million loan from the World Bank to prepare itself to fight forest fires, and our little research team raced to map out the forests that were at greatest risk. In May of 1998, we presented our map of forest-fire risk to the Brazilian Congress, warning the government that forests once burned were more likely to catch fire again in a vicious cycle. As we had seen from previous burns, forest fires toasted the bark

glimpse of the future of the rainforest in a warming world. The water temperature of the ocean off the coast of Peru started to heat up in a particularly severe El Niño episode. El Niño changes atmospheric circulation patterns around the world, making it rainier in some places (like California and São Paulo) and drier in other places (like the eastern Amazon and Borneo). In Paragominas it had rained only four inches in five months, and the trees were starting to show their thirst. During

our monthly measurement of leaf water stress (imagine eight men climbing trees on mountain-climbing ropes, plucking leaves from the branches just before sunrise!), my jaw dropped as I measured each leaf with the same sobering result. The forest had run out of water! Leaf water stress had skyrocketed.

A few days later, it rained three inches, and the drought was over. But what would have happened had the drought continued? Would the forest have shed its leaves,

at the base of trees, condemning many of these giant organisms to slow death, creating gaping wounds in the canopy. As the 1997–1998 El Niño episode roared on, drought, fire, and the risk of further burning came together in a recipe for large-scale forest destruction. More than 15,000-square miles of forest—an area twice the size of Massachusetts—caught fire during this drought episode.

The 1997–1998 El Niño episode finally came to a halt just as we installed the last plastic panels across a patch of rainforest soil, initiating a four-year-long period of reduced rainfall. During the third year of our experiment, which I led together with my long-term friend and colleague, Paulo Moutinho, one of our main predictions fell flat. Instead of small trees succumbing first to the effects of our imposed drought, the largest trees began to die. Deprived of soil water to a depth of 45 feet, the sun-exposed leaves of the tallest trees become particularly vulnerable to tissue damage and death. Like logging and forest fire, a severe drought kills some of the trees that contribute most to the deep, damp shade of the forest interior, and therefore increases the risk of forest fire for years after the drought has gone by.

As I survey the forests of the eastern Amazon from forest trails, small airplanes, buses, or pickup trucks, I see a magnificent ecosystem teetering precariously close to a tipping point. El Niño episodes may become more common in a warming world, some climatologists believe. And in 2005, the warming waters between western Africa and the Gulf of Mexico showed us that there is more to worry about than El Niño. The warming of the tropical North Atlantic Ocean in 2005 gave North America one of its most brutal hurricane seasons, with devastating consequences for New Orleans. This same anomalous warming of the North Atlantic also created a high-air-pressure system above the Amazon that inhibited the rains over large areas of the central and western Basin. Hundreds of riverside villagers were stranded, unable to navigate the rivers for lack of water. Fish kills contaminated water supplies, and palls of smoke provoked respiratory ailments. We don't know the full extent of fire damage

for 2005. But in the southwestern corner of the Amazon, at least a thousand-square miles of forest caught fire.

At some time in the near future, we may see a mega-drought that extends for three years that kills trees and fosters fire across a third or fourth of the Amazon Basin. Every dead tree will slowly release the carbon in its wood into the atmosphere as it decomposes or burns. There are approximately 120 billion tons of carbon stored in the wood of Amazon trees, equivalent to 15 years of today's worldwide, human-induced emissions of carbon to the atmosphere. A catastrophic period of drought and fire could erase the gains made in lowering greenhouse-gas emissions through the Kyoto Protocol, and through the many new initiatives underway in California and elsewhere. And if such a devastating drought crip-

pled the forest's ability to pump vapor into the atmosphere, feeding the rain clouds that supply the entire region, the chances of another mega-drought would become greater.

It is in all of our interests to prevent this scenario of widespread destruction of the Amazon. A promising new system for rewarding those tropical countries that achieve success in lowering their greenhouse-gas emissions from tropical forests could be the carrot that is needed to encourage Brazil and other nations to do what the United States was unable to do: keep most of its virgin forests standing. TAP

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Biodiversity in Jeopardy

There are more life forms in Amazonia than anyplace else. But by the end of this century, there may be many fewer.

BY MICHAEL GOULDING AND ADRIAN FORSYTH

THE AMAZON BASIN IS, ABOVE ALL, our planet's greatest celebration of biodiversity, where for hundreds of millions of years environmental conditions have favored an overall increase in the numbers of species. It is not clear why this has been so. Perhaps the principal factor has been a warm and humid climate, at least in large parts of the Amazon Basin.

Tracing the Amazonian landscape through time, we see huge rivers shifting their courses, rainforests contracting and expanding to the pulse of climatic change, and the evolution of several major ecosystems within the reaches of the world's greatest river network. These factors and others allowed the diversification of both animal and plant species. Indeed, flowering plants have been diversifying there for at least 65 million years. Although the plant species are far less diverse than the

animals, it is the structure of the tropical rainforest that supports the millions of animal species found there.

The giant rivers of the Amazon weave together the ecosystems that support our planet's greatest profusion of life. The reflection of the trees that we see splashed across the water's surface is both literally and ecologically a reminder of how closely linked are the rivers and rainforest. In the Amazon one is unimaginable without the other. Flowing through vast floodplains, the Amazon's various river types include muddy, clear, and black-water tributaries, each with its own chemistry and unique combination of species.

The geography on which the rich biodiversity in the Amazon is expressed embraces five main geologic-ecologic regions: the Andes, Amazon Lowlands, Brazilian Shield, Guiana Shield, and estuary. The shield regions are the ancient