Introduction to the Large-scale Biosphere-Atmosphere Experiment in *Amazonia*

BY REBECCA LINDSEY • DESIGN BY ROBERT SIMMON • DECEMBER 31, 2002

With tributaries extending from the vast savannas to its north and south, the Amazon River runs almost 4,000 miles (1 mile equals 1.6 kilometers) across northern South America from the highland biomes in the foothills of the Andes Mountains to the Atlantic Ocean. It carries twenty percent of all river water discharged into Earth's oceans—ten times the volume of the Mississippi River. If the Amazon River Basin were draped over the continental United States, it would cover more than three fourths of the country.

Introduction: The Large-scale Biosphere-Atmosphere Experiment in Amazonia

Part 1: Escape from the Amazon

Part 2: From Forest to Field

Part 3: Stealing Rain from the Rainforest

Part 4: Defying Dry: Amazon Greener in Dry Season than Wet

From December to May each year, torrential rains and snow melt from the Andes increase the main river channel's depth 30-45 feet (9 to 14 meters), and water backs up in tributaries and inundates forest several miles from the main channel. In the central Amazon Basin alone, the flood waters can cover an area up to 97,000 square miles. The river and the flooded forests then come together as a giant, slow-moving swamp. Surrounding these waters are over 2.7 million square miles (7 million square kilometers) of lush forest exploding with life. In fact, perhaps as much as one half of all life forms on the planet live in the Amazon River Basin.

The Amazon River runs almost 4,000 miles from the Andes Mountains in the west to the Atlantic Ocean in the east. The river basin plays a key role in heat, moisture, and carbon cycles both regionally and globally. The region is also the most biologically diverse location on Earth, supporting perhaps half of all species on the planet.

The Amazon is more than a habitat, however; it is also a climate regulator. Located near the equator, where the sun's daily rays are most intense, the uninterrupted expanse of lush vegetation absorbs incoming radiation and keeps things cool. The forest also absorbs and stores moisture. The Amazon forest canopy is so dense and so biologically productive that scientists have also recognized the region as a key component of the global carbon cycle. The continent-spanning tracts of forest inhale tons of carbon dioxide during photosynthesis and exhale oxygen. With respect to carbon, however, these forests aren't all take. Through deforestation, decomposition, respiration, and export of organic and inorganic matter to the oceans, they also give.

The dense vegetation of the rainforest canopy is a sink for atmospheric carbon dioxide.

Escape from the Amazon

by **Rebecca Lindsey**
design by **Robert Simmon**

April 23, 2003

In this era of heightened concern about the relationship between the build up of atmospheric carbon dioxide and climate change, scientists are working to itemize all the ways carbon moves between the atmosphere and the elements of Earth's surface, including life, water and soil. Forests are of particular interest in large part because many nations now manage the forests within their borders, deciding where and when to harvest trees and when to leave the forest alone. Now those decisions are influenced by the role forests play in the global carbon cycle. Forests' ability to take in and sequester carbon during photosynthesis has ceased to be something we accept without thought; the biological services they provide have instead become a product with a market value to be traded between nations like radio parts or soybeans. Just as humans have turned to forests for fuel, food, and shelter for hundreds of thousands of years, we now look to them to help us compensate for the atmospheric excesses of our combustion-engine civilization.

The Amazon rainforest is a vast area of dense jungle. The vegetation "breathes" carbon dioxide and converts the carbon into biomass—tree-trunks, branches, and leaves. Therefore, the forest acts as a huge reservoir of stored carbon. But other processes, such as respiration and the decay of dead plants, release carbon back into the atmosphere. Scientists are currently studying the forest to learn whether, in the end, the Amazon is a source or a sink of carbon dioxide. (Photograph copyright Digital Vision)

Whether or not forests will respond as we hope is unclear. Factors other than carbon dioxide availability influence rates of photosynthesis—factors such as water availability and heat stress. In addition, the carbon cycle of a forest involves more than just carbon dioxide uptake because forests burn, decompose, and respire, re-releasing some of their carbon stash back into the atmosphere. We must consider the contribution of many processes to the overall cycle before we can say what future role forests will play in the global carbon cycle or how much we can rely on them to absorb steadily increasing atmospheric carbon dioxide.

Perhaps nowhere on Earth do questions about the role of forests in the carbon cycle need answers more than in the Amazon Rainforest. The largest expanse of tropical forest on Earth, the Amazon covers just 5% of the Earth's land surface (neglecting Antarctica), and yet is

Escaping carbon

At first glance, the simplest explanation might appear to be deforestation. When forests are cut down or burned, the carbon stored in the forest biomass is released into the atmosphere. Combined with the other processes that carry carbon out of the rainforest ecosystem —decomposition, respiration, soil and sediment run off into the Atlantic—deforestation might be the big source of carbon scientists are seeking. But calculations suggest otherwise. In Brazil alone, deforestation is proceeding at a rate of about 20,000 square kilometers per year as the Amazon is cleared for farming and ranching (Houghton, et al., 2002), but these losses still do not appear to be large enough to offset the large carbon intake measured by the flux towers.

2000 roll over the image to see change over time

The state of Acre in Brazil, shown in the satellite image above, is undergoing rapid deforestation. Move your mouse cursor over the image to compare the landscape in 2000 with how it appeared in 2002. The tan areas are recently cleared patches. The 2002 image is also shrouded in haze from nearby fires set to clear land. (Images by Clare Averill, NASA JPL MISR Science Team)

If deforestation wasn't the culprit, then how could scientists account for the apparent discrepancy between how much carbon the flux towers indicated was coming into the forest and the lesser amount of carbon actually contained in the biological material? Researchers had no lack of alternative explanations. Maybe the global models were wrong. Maybe estimates of the rates of deforestation were too low. Maybe there was something wrong with how scientists were collecting the flux tower data. A few scientists, though, did not discount the possibility that the Amazon could be hiding a large, yet-to-be-discovered source of carbon emissions. Richey thought he knew where.

"We had been working in the Amazon for almost 20 years, collecting all kinds of river samples, including measurements of the carbon dioxide dissolved in the water. So as far back as 20 years ago, we were publishing papers saying that the amount of carbon in the waters of the Amazon was greater than that in the air. For years I had been listening to the carbon modelers complaining about the discrepancies in the tropics, and I said to myself, 'I know that carbon dioxide is moving out of the water into the atmosphere.' But at that time the scientists doing the carbon modeling didn't talk to the people doing the flux tower measurements, and they didn't talk to those of us who were down on the water."

LBA brings the right scientists together

But then in 1998, the Brazilian science community, joined by an international team of scientists, launched the Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA). Their aim was to study how Amazonia functions as a regional entity within the larger Earth system and how changes in land use and climate will affect the biological, physical, and chemical functioning of the region's ecosystem. With the Amazon as their laboratory, scientists have been studying climate, atmospheric chemistry, the carbon cycle, nutrient cycling, land surface hydrology and water chemistry, land use and land cover, and the interaction of humans with the landscape.

Richey credits the LBA project for bringing a diverse group of scientists together and encouraging them to speak a common language. It was on a return flight from an LBA conference that Richey began a dialogue with a carbon cycle modeler. He says,"On the plane we started comparing notes. I realized that we had always talked in terms of pressures of carbon dioxide, and they spoke in terms of mass, so many tons of carbon in and out of the ecosystem each year. I realized we would need to put our results into that common language."

Although direct measurements of the air in the Amazon [from flux towers (left)] showed the forest removing large amounts of carbon dioxide from the atmosphere, mathematical models of the global atmosphere showed the Amazon as a source of CO_2. Jeffrey Richey and a team of scientists had been studying the region's rivers and streams for 20 years, and knew that high concentrations of CO_2 were dissolved in the water (right). Perhaps the excess CO_2 was coming from the Amazon River and its tributaries. [Photographs courtesy Michael Keller, USDA Forest Service Institute of Tropical Forestry (right), and Jeffrey Richey, University of Washington (left).]

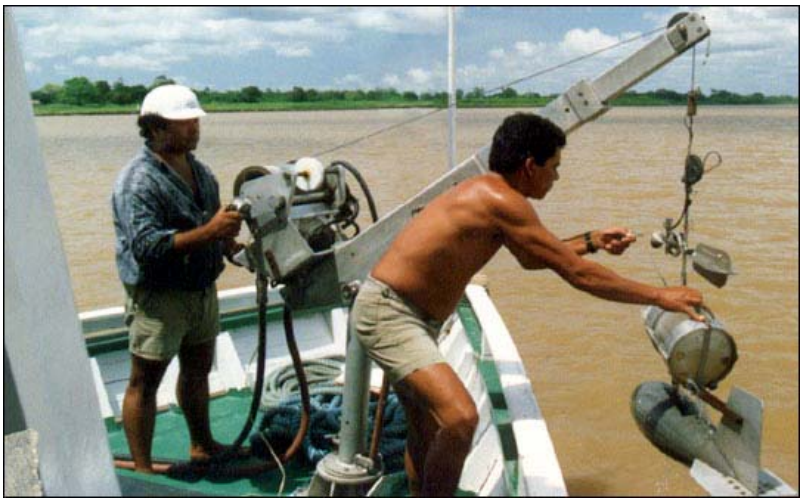
Richey knew that what they needed was a grand total: how much total carbon was emitted from water surfaces (a process called evasion) across the Amazon every year. To get a grand total, they required two pieces of information; as many measurements as they could get of the amount of carbon dioxide released by numerous areas within the basin and an estimate of the total surface area covered by water in the Amazon. To come up with these numbers, Richey and his colleagues made use of data sources that ranged from low tech— more than a decade's worth of air and water samples collected from the bows of small fishing boats—to a sophisticated, satellite-based radar.

Small teams of scientists working in remote reaches of the Amazon discovered that large amounts of carbon dioxide were escaping from the surface of Amazon flood waters. Carbon dioxide was trapped by bowls turned upside down over the water. (Photograph courtesy Jeffrey Richey.)

Using the Right Tools

Richey already had a lot of the river water samples he needed. Between 1982 and 1992, he and his colleagues had periodically gone out on six-week river cruises on a 60-foot, double-decker research boat. In describing those thousand-kilometer expeditions, Richey says, "The Amazon is almost beyond anything you can imagine. There's this vast life and energy surrounding you. The sky is moving. The river is swirling and churning. There

are birds everywhere. Then you get off the big boat and into outboards to go into the narrower floodplains, and you are overwhelmed by the smell of all the vegetation. And all day, there's the pressure of the sun."



Richey's team measured the carbon dioxide dissolved in the Amazon Basin's rivers by sampling the water directly. A decade of river cruises gave the researchers extensive knowledge of the region. (Photograph courtesy Jefferey Richey, University of Washington)

In addition to the standard, canned, camp fare you'd expect on a month-long research venture into the depths of the Amazon, Richey says the crew ate delicious local food, especially the fish they bought from local fisherman. The trips were not always idyllic, however. The researchers had one of their scarier moments after being confronted by a local tribe who mistakenly thought the researchers had arrived to take them away and claim a bounty on the tribe offered by drug traffickers. Richey and his colleagues beat a hasty retreat, more than willing to sacrifice a few data points to preserve the peace.

Richey and his colleagues collected more than 1800 river water and air samples within the central Amazon River Basin. In some cases, they used huge winches to haul up samples from deep in the river. In other cases, they captured gas emissions from the water surface using what Richey called "floating dishpans," and described as inverted bowls placed over the water.

The second piece of information Richey needed was a good estimate of just how big an area was covered by water during the year. The Amazon may be perpetually wet, but it is wetter at some times than others. From December to May each year, torrential rains and snow melt from the Andes increase the main river channel's depth 30 to 45 feet, and water backs up in tributaries and inundates forest miles from the main channel. The river and the flooded forests, called várzea in Portuguese, become a giant, slow-moving swamp. Richey needed to know how big.

Dry Season (June–November)

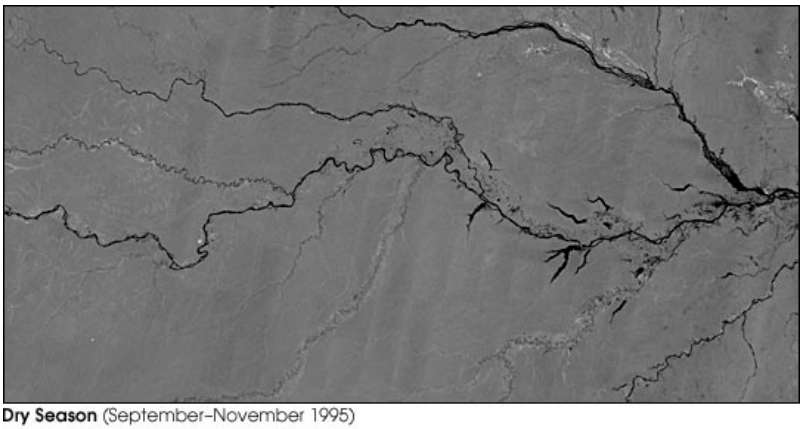
Wet Season (December–May)

The area covered by water in the Amazon isn't constant; it varies wildly with the change of seasons. The várzea —flooded forest—is inundated every May by rain and Andean snowmelt. (Photographs courtesy Max-Planck-Institute for Limnology)

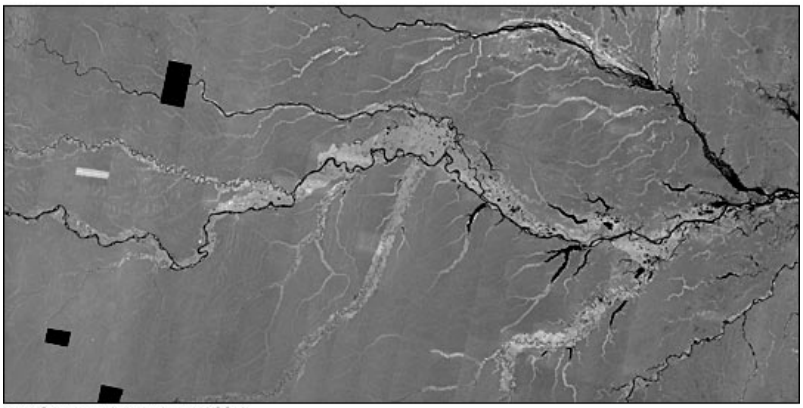
Given the immense area under study, an afternoon trek through the jungle with a camera in hand was out of the question. Satellite mapping was the only real possibility; satellites such as NASA's Landsat series had been mapping the Amazon basin for years in true- and false-color imagery. Optical sensors like those on Landsat, which work like digital cameras, have a serious limitation, however. If there is one thing that you can count on in the Amazon during the wet season, it's rain. At precisely the time of year when Richey needed imagery to reveal the extent of the flooding, the rain clouds hid the forests from a satellite's view. To map the flooded Amazon forests, Richey needed a remote-sensing device that could see through clouds. He turned to radar.

Seeing Through Clouds

Unlike traditional optical sensors, radar is considered active as opposed to passive remote sensing. Instead of passively recording how much energy is being reflected by or emitted from the Earth as the spacecraft travels overhead, radar works by sending out a pulse of radio waves toward a target and then recording the strength and return time of the signal as it bounces back. That information tells the scientists both how far away the target is and what the surface looks like, since different surfaces will absorb and reflect the pulse in different ways.



Dry Season (September–November 1995)



Wet Season (May-June 1996)

Radar maps of the Amazon Basin reveal the seasonally flooded forest. In the pair of images above, black represents permanent waterways, dark grey represents forest, and light grey represents flooded areas. (Images based on data provided by the Global Rainforest Mapping Project)

Although LBA is a Brazil-led study, it is an international affair. The National Space Development Agency (NASDA) of Japan mapped the Amazon floodplain as part of their Global Rainforest Mapping Project, using radar data collected by the Japanese Earth Resources Satellite (JERS-1). As the satellite mapped tropical rainforests around the globe, different groups around the world became responsible for processing the data and making them available to the scientific community in an easy-to-use format.

Bruce Chapman is a senior engineer at NASA's Jet Propulsion Laboratory (JPL) in California, which is the organization selected by NASDA to handle the data coming in from South America. Chapman was a principal investigator on the project. "With an optical sensor," he says, "it can take years to create a cloud-free image of the Amazon. Even the supposedly 'cloud-free' image still has some clouds because there are places in the Amazon where the clouds just never go away. Radar wavelengths penetrate the clouds and provide a detailed image of the forests below. The radio waves can even penetrate the forest canopy and reveal the layers of structure within the forest right down to the ground."

It's this ability to see the underlying structure that enabled them to map the extent of the flooding. The water underlying the forest canopy provides a kind of amplification of the returned radar signal. Explains Chapman, "The water underneath the canopy provides something we call a 'double bounce reflection.' This double bounce occurs when the radar waves bounce off two perpendicular structures: the very reflective surface of the water and the tree trunks. This double bounce makes the return signal very bright. When we see that really bright signal in the Amazon, there is a good chance there are partially submerged trees."

Flooded areas appear bright to radar because the radar waves are reflected directly back at the sensor. The first bounce, off the water surface, is away from the

Making the maps

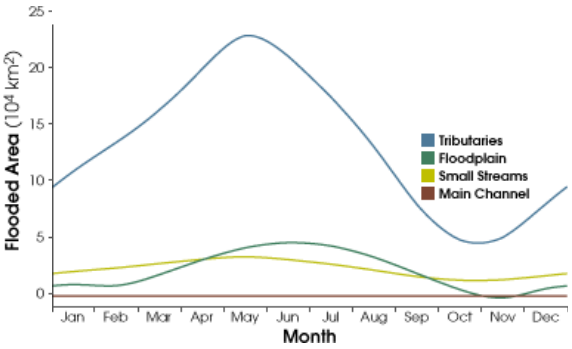
The mapping of the Amazon took place in two phases: one data collection for the dry season and a second one for the wet. The first strip of radar data was obtained on September 27, 1995, over the east coast of South America. The satellite mapping progressed about 75 kilometers westward each day for the next 62 days, with the last strip collected over the west coast in mid-November. Beginning May 4, 1996, the satellite mapped the Amazon in flood. The picture was complete by July 3. Chapman and his team at JPL made the final maps available to the scientific community in March 2001.

Even with the radar data, though, there were limitations. The radar could only see rivers and streams at least 100 meters wide, but hundreds, possibly thousands of small streams branch across the Amazon. “To get those streams,” explains Richey, “we had to drill down even further, using Geographic Information Systems (GIS) data sets that had been collected over the years.” For the smallest streams they had computer models predict the volume and area based on topographic and geologic features.

sensor, but the second bounce, off the tree trunks and canopy, redirects the beam back towards the source. (Photograph courtesy Jeffrey Richey)

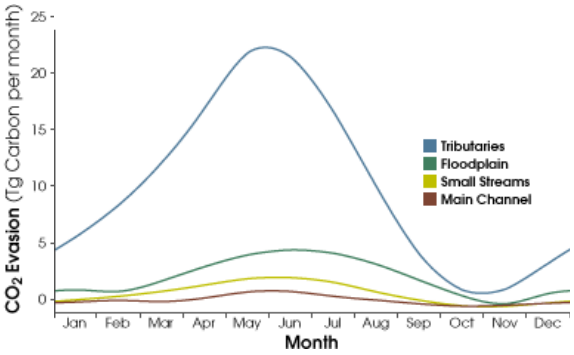
Putting Together Maps and Measurements

Despite the aid of satellite data and years of observations, Richey and his colleagues couldn’t hope to study the whole Amazon. Instead, they focused their efforts on a large area in the central Amazon basin. They categorized the waters of the 1.77-million-square-kilometer study area into four geographic regions based on the hydrological characteristics: the main Amazon channel, the main channel floodplain, tributaries greater than 100 meters wide, and tributaries less than 100 meters wide. The region was further subdivided into up-, mid- and downriver regions. Based on the carbon dioxide detected in the river samples from each of these categories, they came up with an estimate for the entire study area.



The area covered by the Amazon River and its tributaries more than triples over the course of a year. In an average dry season 110,000 square km of land are water-covered, while in the wet season, the flooded area of the Amazon Basin rises to 350,000 square km. (Graph adapted from Richey, Melack, Aufdenkampe, Ballester, and Hess)

Richey said they had suspected for years that the amount of carbon dioxide evasion could be large, but until they could combine their ground-based measurements with the satellite maps of the total flooded area, they had no hard evidence, no “smoking gun.” When the amount of carbon dioxide emitted from the sampled water surfaces was extrapolated to the entire flooded area within the study site, it totaled 120 million grams (264,550 pounds) of carbon per square kilometer per year. A rough estimate for the amount of carbon given off by the entire Amazon River basin was half a gigatonnne of carbon every year—a mass of carbon equivalent to more than 90 million adult elephants!



The rivers in the Amazon Basin carry a large amount of dissolved carbon dioxide gas, created by rotting leaves and other sources in the forest upstream. As the river system floods each year, some of this carbon dioxide is released into the atmosphere, peaking at a level of about 35 teragrams of carbon per month. (Graph adapted from Richey, Melack, Aufdenkampe, Ballester, and Hess)

Says Richey, "When we put our measurements together with the satellite-based flood maps, we got an estimate of carbon dioxide emissions that was greater than 10 times the amount of carbon that washes out to sea in the river outflow. Hydrologists had long thought that the most important role of river systems in the global carbon cycle was in the carbon that flowed out to sea as dissolved organic and inorganic compounds. And now we had an estimate that the carbon dioxide flowing into the atmosphere directly from the river surface was almost 13 times larger than that amount." For the first time, there was solid evidence of a large carbon source within the forest sink.

Identifying the Source of the Source

The carbon in the rivers comes from a number of places. Richey and his colleagues' believe that most of the carbon originates in the non-flooded, upland forests. Accounting for 35 percent of the total, they believe, is forest litter that washes down from highland forests. The litter decomposes, giving off carbon dioxide. Another 25 percent of the carbon comes into the system directly as carbon dioxide when plant and tree roots give off carbon dioxide during respiration. The carbon dioxide becomes dissolved in groundwater that flows into streams and rivers. Another 15 percent comes from carbon-containing compounds that leach out of soil, leaf litter, and other biological matter. Those dissolved organic carbon compounds get metabolized by river life, ultimately returning to the atmosphere as carbon dioxide.

By identifying the carbon dioxide being transferred from the rivers of the Amazon Basin to the atmosphere, scientists are enhancing their understanding of the role the Amazon plays in the global carbon cycle. This understanding will help clarify how natural and human-caused changes in the Amazon could change the world. (Photograph courtesy Jeffrey Richey)

Richey estimates that only about 25 percent of the carbon given off by the Amazon River and its tributaries actually originates within the river itself, mostly in the form of aquatic vegetation that first fixes carbon dioxide during photosynthesis and then respires some of it back into the water. He admits those numbers are only estimates at this time. Despite the surprising discovery of this large source of carbon emissions, he says, so far the scientific community doesn't seem bothered by the magnitude of his estimate. "There is definitely a sense of 'here is a missing piece' of the tropical carbon budget puzzle."

Answers Produce More Questions

Where that carbon is coming from is more hotly debated. If most of the carbon dioxide released from the Amazon waters comes from carbon originally absorbed by the upland forests and washed down into rivers and streams, as Richey believes, then it would represent a real carbon loss from the ecosystem. But if it turns out the carbon dioxide is produced by vegetation in the river and in the adjacent flooded forests and lakes, rather than the upland forests, then the large emissions only counterbalance a large carbon intake by the aquatic vegetation. The source of the carbon dioxide seeping out of the Amazon waters is the subject of several ongoing studies.

Richey's enthusiasm for the project and his excitement about the results don't seem to have dimmed since the paper was published in the journal Nature in April 2002. "This study was a terrific assemblage of water chemistry data, GIS, theory, remote sensing, and tower dynamics. That's why this was so fun—the integration—all these disciplines coming together to work on a problem." The implication is that the coupling between the land and the atmosphere, and also between the terrestrial Amazon and the aquatic Amazon, is tighter than scientists previously thought.

Those who say that for every question science answers, it generates a dozen more can find evidence in Richey's work. Richey himself is already thinking ahead. He wonders about the effect on this source of carbon from global warming and land-use change. He's also beginning to think globally, and has also begun planning a similar study of the rivers and rainforests near the Mekong River in southeast Asia. And he's not done with the Amazon yet either. Says Richey, "Not all the data we used in this study was gathered specifically to answer this question. Now we have to go back and get better, more detailed measurements, specifically targeted to answering our questions."

References:

1. Richey, J. E., Melack, J.M., Aufdenkampe, A.K., Ballester, V.M., and Hess, L.L. (2002) Outgassing from Amazonian rivers and wetlands as a large source of tropical CO2, *Nature*, 416: 617-620
2. Houghton, R.A, Skole, D. L., Nobre, C.A., Hackler, J.L., Lawrence, K.T., and Chomentowski, W.H. (2002) Annual fluxes of carbon from deforestation and regrowth in the Brazilian Amazon, *Nature*, 403: 301-304

Resources:

1. Amazon Facts from the Smithsonian National Zoo.
2. LBA-ECO Website

From Forest to Field:
How Fire is Transforming the Amazon

by Rebecca Lindsey • design by Robert Simmon • June 8, 2004

Before widespread human settlement began to encroach on the borders of South America's Amazon forests, there was no such thing as an Amazon fire season. Now, fire may pose the biggest threat to the survival of the Amazon ecosystem.

A fire sweeps through a portion of the Amazon Rainforest, reducing the vegetation to ash. Once rarely touched by fire, the portions of the Amazon near areas of human development are becoming increasingly susceptible to damaging fires. (Photograph copyright Woods Hole Research Center)

Slash-and-burn agriculture converts forest to farm land, but that obvious destruction is only the beginning. Intentional fires get out of control and burn through the understory of nearby forests, killing, but not completely burning small trees, vines and shrubs. The dead and dying trees collapse, spilling firewood and kindling to the ground and ripping a great tear in the tent of the forest overhead. Logging has a similar effect. The intense tropical sun, previously deflected by the green canopy, heats the forest floor, pushing fire danger even higher. Smoke hangs over the forest and suppresses rainfall. In this damaged, fragmented landscape, the onset of the natural dry season becomes ominous. The El Niño-driven droughts that typically arrive a couple of times per decade become devastating.

Stealing Rain from the Rainforest

by Rebecca Lindsey · design by Robert Simmon · March 8, 2005

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Ecologist Dan Nepstad of the Woods Hole Research Center is engaged in an activity that might seem crazy for someone who cares about forests as much as he does. For the past two years, this veteran of tropical forest research has been stealing the rain over two and half acres of forest in the eastern Amazon.

Dan Nepstad and his colleagues constructed a unique structure, similar to a greenhouse, to deprive a small plot of the Amazon Rainforest of rain. This seemingly bizarre activity was part of a study on the effects of drought on the forest. [video (4.5 MB Windows Media)] (Photograph courtesy Dan Nepstad, video courtesy Paul Lefebvre)

Strangely, no one seems to mind. None of his colleagues, including fellow Amazon researcher and remote-sensing expert Greg Asner of the Carnegie Institution and Stanford University—whose career in tropical forest research began with the environmental group The Nature Conservancy—has tried to stop him. In fact, if you ask Asner, he'll say the whole thing is a great idea.

Nepstad's 'grand theft water' isn't supporting an exclusive tropical resort or even a hydroelectric project. In fact, he has no need for the water at all. He just doesn't want the forest to have it. Nepstad and Asner want to know how much drought the forest can take before it begins to show signs of stress, what those signs are, and whether any of them can be detected from space.

In the always-green Amazon Rainforest, signs of drought are rarely obvious. To simulate the severe droughts the Amazon can experience during El Niño events, scientists diverted rainfall from an experimental forest in Brazil and then observed the impacts from ground-level and from space. (Photograph courtesy 3rd LBA Scientific Conference)

"We started thinking about simulated drought experiments back in 1994, when the Amazon was coming out of a major drought caused by a severe El Niño, and the forest almost completely ran out of water," Nepstad says. The fact that the Amazon experiences drought often comes as a surprise to people. It's the rainforest, after all; doesn't it rain all the time?

"That's one of the most fascinating things about the Amazon," explains Nepstad. "The east and southeastern parts of the forest actually go months each year with little or no rain. The trees survive by tapping soil moisture as far down as 20 meters." During strong El Niño events, wet-season rainfall decreases, making the dry season even drier. Under those conditions, even the deep-rooted trees begin to suffer.

Nepstad is concerned that longer and more severe droughts hover on the Amazon's horizon. Some scientists are predicting that El Niño events will become more frequent and severe as Earth's climate warms. Large-scale deforestation and smoke from biomass burning interfere with local cloud formation and rainfall. Identifying the precise signals of a drought-stressed forest would benefit the region's farmers, timber operators, fire planners, and conservationists. Being able to detect those changes from a satellite would be a huge advantage; the Amazon is enormous and in many places still remote and difficult or impossible to survey on foot.

Although the Amazon Rainforest is evergreen, many places in the east and southeast go months each year with little or no rain. Vegetation survives these natural droughts by tapping moisture deep in the soil. The drought simulation occurred at an experimental site in the Tapajós National Forest in Brazil, near where the Tapajós River joins the Amazon. (Map by Robert Simmon)

Nepstad's and Asner's shared interests in forest ecosystems led both of their careers to Brazil's Large-scale Biosphere-Atmosphere Experiment in Amazonia (LBA, for short), the largest cooperative international scientific project ever to study the interaction between the Amazon Forest and the atmosphere and ultimately, the climate. NASA's LBA-ECO program is one of numerous participants in the effort. The scientists funded under the LBA-ECO program concentrate on the processes and effects of land use change, often using NASA satellite data to add a wider view to what they observe on the ground.

"Through LBA," Asner says, "Dan and I realized we had common research interests. I was working on how to use remote sensing to describe the structure and function of forest canopies, and he was working on the impact of drought, fire, and logging. We realized that the drought experiment he was planning was the perfect opportunity to try to find some field-based and remote-sensing indicators of drought stress."

▶ It's a Jungle out There

It's a Jungle out There

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This perfect opportunity wasn't going to just fall out of the sky, though. It would require tremendous creativity, ingenuity, and sweat from Nepstad and the local carpenters, self-educated engineers, and laborers he hired to help figure out how to exclude rainfall from a 100-meter-by-100-meter (1 hectare) plot of rainforest.

Hand-crafted wooden walkways gave scientists access to the upper levels of the forest where they could measure the effects of drought on the rainforest canopy. (Photograph courtesy Paul Lefebvre)

It might seem easier to just go out and find a location that was experiencing a naturally occurring drought and then compare it to a location that wasn't. The trouble with that idea is that the plots need to be similar to each either other in as many ways as possible—from the number and kinds of trees, to topography and altitude, to soil type—so that the scientists could be sure any differences between them were due only to drought stress. In a place as diverse as the Amazon, that kind of similarity is rare. Once you found two such places, you might have to observe the two for years—perhaps a lifetime—in the hope that at some point, one would experience a drought and the other wouldn't.

"If you look at all the trees in a 1-hectare plot with a minimum diameter of say, 10 centimeters, at least 2/3 of those trees will be a single individual of a species. That's how diverse the place is. Just to find two 1-hectare plots that had several species in common, we had to survey 22

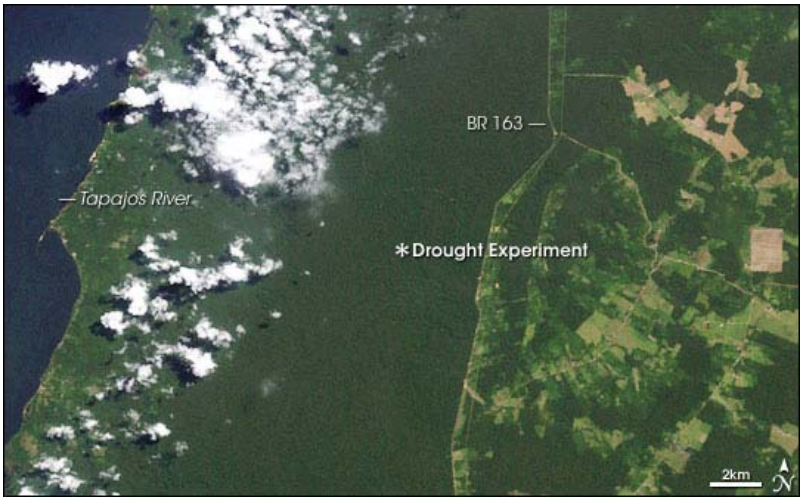
hectares," explains Nepstad.

Then the sites faced another test. "The first big challenge at any potential site," he continues, "was whether we would be able to dig a 10-meter pit in the ground so that we could measure soil moisture at various depths. I had to carry along an auger to test-drill at potential locations."

A researcher descends into a 10-meter-deep pit to measure soil moisture. Normally, rainforest trees survive months of seasonal drought each year by drawing on water stored deep in the soil. During severe droughts, however, the soil can become so dry that even deeply rooted trees suffer. (Photograph courtesy Dan Nepstad)

There was no guarantee that the ground would be suitable for digging. Almost the entire Amazon Basin was once covered with a vast lake, and the region's soils are dense clay formed from sediments that settled to the bottom over hundreds of thousands of years. Asner laughs as he says he is glad his part of the project didn't involve much digging. "In the wet season, the soil turns to a thick clinging mud that sticks to shovels and boots and everything. In the dry season, it turns to brick."

Asner faced challenges of his own, though. The biggest problem with remote sensing in the Amazon is the clouds. "Even if imagery is mostly clear," says Asner, "it seems like there will always be a cloud in the area you want [to see]. At some locations you might get only one or two cloud-free observations per year, which isn't much, but it turns out to be sufficient for land use change and selective logging studies. It works pretty well for drought stress, too, because the one to two cloud-free overpasses are in mid to late dry season, which is the most drought-stressed time of the year for the forests."



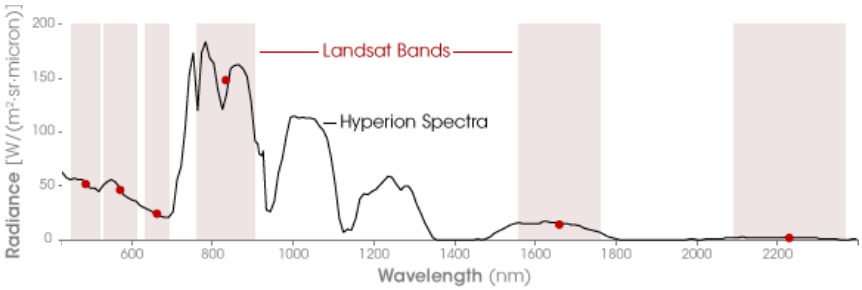
About 50 kilometers south of where the Tapajós River joins the Amazon River, the Tapajós National Forest lies between the Tapajós River in the west and the Santarém-Cuiabá Highway (BR-163) in the east. Large, rectangular clearings punctuate the forest beyond the highway. The Tapajós National Forest is a 6,000-square-kilometer protected area where international teams of scientists carry out research into how the Amazon responds to human and natural disturbances. (NASA image by Robert Simmon, based on data Landsat 7 data provided by the Global Land Cover Facility)

In with the New

The satellite observations for the study came from NASA's first satellite-based hyperspectral remote sensor. The difference between a hyperspectral sensor and a multispectral sensor is that a multispectral sensor detects electromagnetic energy in a sampling of broad slices (groups of wavelengths) of the spectrum while a hyperspectral sensor detects hundreds of very narrow slices of the spectrum that are contiguous, meaning that one slice touches the next, leaving no gaps. Called Hyperion, the hyperspectral sensor is flying on the Earth Observing-1 satellite. Hyperion is one of several new sensors that NASA is testing in an effort to produce smaller, less expensive devices with more capabilities than its current generation of sensors.

The current Landsat satellites, for example, whose observations have been the centerpiece of high-resolution land cover and land cover change mapping for years, only collect observations of 7 different spectral bands (the broad slices of wavelengths of electromagnetic energy described above) reflected or

emitted from Earth. Hyperion detects 220. If a multispectral sensor can be compared to you standing at a paint counter in a home improvement store asking for white paint, a hyperspectral sensor would be the clerk asking, “Did you want antique white, or colonial white, or off-white, or eggshell white, or ...?”



A hyperspectral sensor like Hyperion observes energy in a series of adjacent, narrow slices of the electromagnetic spectrum. Plotted on this graph, Hyperion’s observations appear as a continuous black line. Multispectral sensors like Landsat detect a single, average value (red dot) for a block of wavelengths (pink rectangles). For wavelengths near 800 nanometers, for example, Hyperion detects several peaks and valleys in the energy reflected from a surface, while Landsat records a single measurement. (Graph by Robert Simmon, based on data provided by the EO-1 science team)

With all those wavelengths to choose from, Asner had a much better chance of detecting the changes in pigment activity, leaf area, and carbon balance that he suspected would change when the forest got stressed by drought. “The problem with remote sensing of vegetation conditions in the Amazon—well, aside from the clouds—is how lush everything is,” says Asner.

Most satellite-based indicators of vegetation describe vegetation “greenness,” which is a general characteristic of vegetation that results from leaf area, canopy cover, and architecture. Greenness indicators are based on the relative amounts of visible light and infrared light being reflected from the forest. Chlorophyll and other pigments in the plant leaves absorb visible wavelengths (except green), while the chemicals that make up the leaves’ cell structure reflect near-infrared light. The trouble is that because it is so green in the tropical rainforest, the signal can get “saturated,” which means that above a certain level of greenness, it all looks the same to the satellite.

Asner decided to test the traditional vegetation indicators against some that used the new information provided by Hyperion to see which ones did the best job of detecting the changes in vegetation brought about by Nepstad’s simulated drought. In addition to two traditional greenness indicators, he tested three new indicators that could only be made from hyperspectral observations: one that was sensitive to the amount of a chlorophyll-helper pigment called xanthophyll, one that was sensitive to a pigment called anthocyanin, and one that was sensitive to the water content in the leaves of the forest canopy.

Stealing the Rain

While Asner was getting familiar with the new kinds of data coming from Hyperion, and designing and refining computer programs to process the observations and calculate the different vegetation indicators, Nepstad had located a suitable pair of sites in the Tapajós National Forest, a managed forest south of Santarem, Brazil, where the Tapajós River joins the Amazon. He was busy figuring out how to temporarily thwart Mother Nature.

Scientists prevented rain from reaching the ground in one area (drought plot) and allowed rain to fall normally in another (control plot). Although the forest looks uniform from above, species diversity is so high that scientists had to survey 54 acres of tropical forest in order to find two, 2.5-acre plots with enough tree species in common for a good comparison. (Image by Robert Simmon, based on IKONOS data copyright Space Imaging)

"I just love that kind of thing," Nepstad says of the challenge of devising a plan to prevent rain from reaching the rainforest. "Challenging" doesn't seem like a strong enough word to describe the situation. "We came up with panels—roofing plates that you can get at local hardware stores—suspended on a wooden structure [about one and a half to two meters off the ground] and tilted to run off into gutters. Each panel was half a meter by 3 meters, and there were 5,600 of them, made out of essentially clear, greenhouse plastic. Then there were 1,700 meters of gutters--a mile of gutter! All that flows into a trench around plot. The trench is lined with plastic, and the water flows off site into a gully about 300 meters away."

The LBA team built a system of panels, gutters, and trenches to steal the rain from the Amazon Rainforest. Clear greenhouse plastic wrapped around wooden frames deflected rain as it fell ...

... into a network of gutters ...

... that drained into a narrow trench, which carried the water off the site. (Photographs courtesy Dan Nepstad)

To minimize damage to the forest during construction, the 1- to 2-meter-deep trenches around the plot were dug by hand—all 1,500 meters of them. “Of course, as we dug them out, they became great congregating places for every kind of snake you can imagine, boa constrictors, everything,” says Nepstad with a short laugh.

Snakes weren’t the only animal visitors. “With the volume of wood and other materials we were bringing in with trucks, we quickly created lakes in the road, and pretty soon we started seeing eyes in them.” The eyes belonged to caiman, a kind of crocodile. “A number of times the workers would be hauling wheelbarrows of dirt from the trenches out to a pile, and find jaguars sitting on the dirt pile, staring at them.”

Prolific native wildlife frequently crawled in and out of the study area. This caiman may look threatening, but it’s only about 30 centimeters (12 inches) long. (Photograph courtesy Paul Lefebvre)

“In all we probably brought in a volume of wood equal to about thirty percent of what was there in the forest itself. I would say about 100 tons of wood was brought in from local, legal,” he stresses, “saw mills. The people who were bringing in all this wood thought we were crazy.”

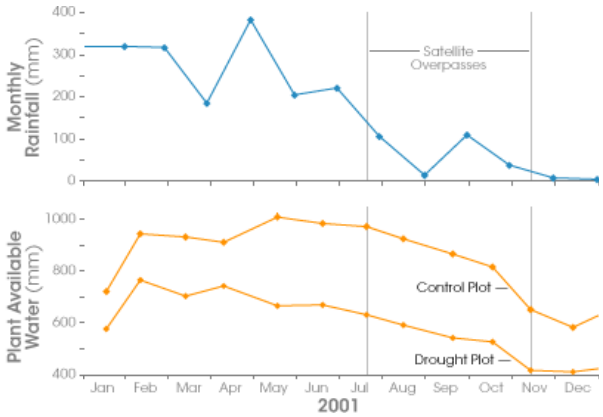
Aside from the trenches they dug to divert water from the site, they also had to dig out 11-meter pits so that they could measure soil moisture at various depths throughout the course of the experiment. “It took three people six weeks to dig each pit, and there were ten of them. At the height of the construction, we had about 45 people employed at the site, and it took about a year and half to set it all up.”

The team spent about a year establishing a set of baseline measurements for 12 characteristics in each plot: rainfall, soil moisture, pre-dawn and mid-day leaf water potential (indicates water stress), litterfall (leaves, twigs, flowers, etc, dropped from the trees to the ground), litter decomposition, leaf area and canopy openness, photosynthesis, flower and fruit production, stem growth, stem respiration (the release of carbon dioxide back into the atmosphere as the tree consumes the sugars and starches it creates during photosynthesis), gases emitted from the soil, and solution chemistry (the different kinds of chemicals that leach into rainwater as it drips down through forest and onto the ground).

Artificial El Niño Gets Underway

By January 2001, the experiment was officially underway. Between January 7 and May 31 about 1,368 millimeters of rain fell over the two sites. Over the course of the wet season, rainfall averaged 9.5 millimeters per day, and the structure Nepstad and his crew had constructed diverted about 50 percent of that from the site, bringing the average down to 4.7 millimeters of rain a day, simulating El Niño drought conditions.

After the wet season ended, the panels were removed. As the dry season progressed, the effects of the rainfall diversion became obvious. By the end of the dry season in November 2001, the amount of soil water available to plants at depths between 0 and 11 meters in the “drought” plot was several hundred millimeters less than the control site, where Nepstad didn’t interfere with the normal rainfall. Leaf area was 17 percent lower than it was at the control site, and mid-day leaf water potential was 30 percent lower.



At the field experiment site, rainfall (top graph) began in January, peaked in May, and dropped off dramatically in July. Plant available water (bottom graph) increased and remained high at the control site (top line) throughout the rainy season, while at the drought site (bottom line), available water was already declining by mid-February, bottoming out at 400 millimeters by the end of the dry season in December. Hyperion collected data over the plots in July and November (grey lines). (Graph courtesy Asner et. al.)

Not surprisingly, all this stress affected tree growth. Net primary production (the total amount of carbon that winds up in trees as a result of what they take in during photosynthesis minus what they give off during respiration) was almost thirty percent less in the drought plot than in the normal plot; the mass of carbon in the control plot increased by 2.6 megagrams, while in the drought plot, it increased by only 1.9 megagrams.

The fact that drought interfered with the tree growth isn't surprising. What is surprising, says Nepstad, is where in the tree this slow-down occurs. "We thought that early drought stress would show up first in leaves—that leaf area would decrease significantly and that litterfall would increase as leaves died and dropped off the trees," said Nepstad. "Instead, we found only small decreases in leaf area, and litterfall actually decreased. It turns out that wood production is the most sensitive to drought stress. Trees just stop growing in diameter, which has important consequences for timber production."

Scientists were surprised to discover that their simulated drought decreased wood production more than it did leaf area. Scientists numbered some individual leaves (top image) to monitor leaf area and mortality. Scientists also measured the girth of tree trunks (bottom image) over the course of the experiment. (Photographs courtesy Paulo Brando)

The second of Nepstad's two big surprises was which trees were most likely to die as a result of the drought stress. It seemed logical that a smaller tree would have a harder time in a drought than a large tree, since the smaller tree's root system couldn't reach as deeply into the soil for water as a larger tree's could. Instead, says Nepstad, "the first trees to die are the big ones, probably because they are in the sun high in the canopy."

Before the experiment, the scientists thought that bigger trees, with their larger root systems, would survive the drought better than smaller trees. Instead, they discovered that the big trees that extend above the forest canopy (pictured at left) were the first to die. (Photograph courtesy 3rd LBA Scientific Conference)

Asner's analysis of the Hyperion data confirmed that the commonly used indicators of vegetation greenness and leaf area just weren't sensitive enough to detect the small differences against a background of such lush vegetation. When he calculated net primary production (net carbon intake) based on the traditional greenness observations collected by Hyperion, the results suggested that the carbon content in the drought plot and the control plot were the same.

NPP Drought:Control Ratio	July	Nov.	2001
Greenness	0.99	0.98	0.98
Greenness and Pigments	1.0	0.83	0.85
Canopy Water	1.0	0.49	0.69
Canopy Water and Pigments	1.0	0.42	0.67
Field Measurements	—	—	0.73

The indicators that made use of the new hyperspectral information from Hyperion were much more successful at detecting the changes in carbon content brought about by drought stress. When Asner factored in observations of xanthophyll pigment activity (increased xanthophyll activity is a sign that a tree is using light efficiently), anthocyanin pigment activity (reddish anthocyanin pigments are most visible in newly formed leaves and buds), and canopy water content, the satellite-based calculations of net carbon intake came very close to matching the growth that had been measured on the ground.

Based on field measurements, net primary production (NPP) at the drought site was 73 percent less than the control site in 2001 (bottom row of table). Rows 2-4 show the ratio of NPP at the two sites estimated from different types of satellite observations in July, November, and for the entire year. Estimates based on hyperspectral observations of chlorophyll-helper pigments and canopy water content matched the ground-based measurements more closely than did the estimate based on greenness alone. (Table courtesy Asner *et al.*)

Defying Dry: Amazon Greener in Dry Season than Wet

by Rebecca Lindsey • design by Robert Simmon

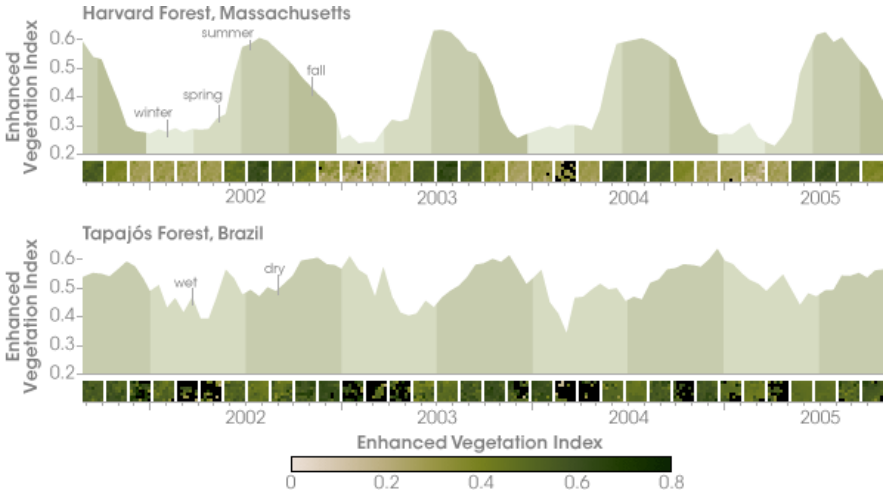
June 30, 2006

▶ 2

Layer upon layer of vegetation stretches from the forest floor to the top of the Amazon Rainforest canopy. Surprisingly, parts of this lush forest go several months each year with little or no rain. The forest actually greens up in the dry season, due to sunny days and water sucked up from deep in the soil by long roots. (Photograph copyright Naadir Jeewa.)

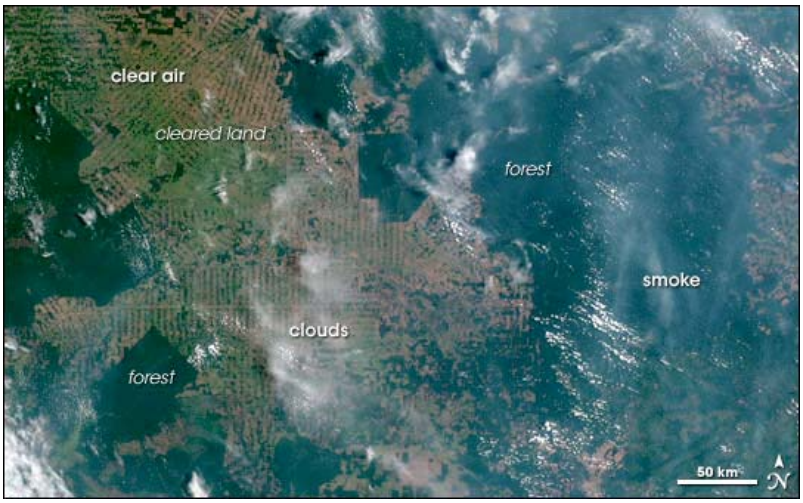
When Alfredo Huete saw Scott Saleska's poster presentation at a meeting of the American Geophysical Union in 2002, he felt like he had been vindicated. Several years before, Huete had been sponsored by NASA to develop techniques for mapping global vegetation using data from a new sensor planned for two of the space agency's upcoming Earth-observing satellite missions. For several years after Terra, the first satellite, launched in 1999, the University of Arizona remote-sensing ecologist had been worrying over the data processing and mapping technique he and his team had proposed.

For nearly two decades, scientists had been mapping global vegetation patterns using a vegetation scale, or index, based on data from a series of satellite sensors operated by the National Oceanic and Atmospheric Administration. The NASA sensors built on and even surpassed the capabilities of the previous sensors, but still, Huete had to deal with a new kind of satellite sensor, a new method for producing the vegetation maps—and the awareness that he was making a product that would go out into a global research community with NASA's name on it. "I felt a lot of pressure," Huete says.



Satellite vegetation maps should match well-known seasonal changes in ecosystems. Satellite measurements collected over ground-based research sites in Massachusetts (top) and Brazil (lower) are shown here as graphs and as a filmstrip of pictures. At Harvard Forest, the seasonal (48-day) satellite observations matched the scientists' expectations: the numbers were highest and the pictures were greenest in summer, lowest and brownest in winter. But over the Amazon, numbers on the graph and the greenness in the pictures went up during the dry season—when scientists expected the forest to be under stress. (Map by Robert Simmon and Jesse Allen, based on data from the Oak Ridge National Laborary DAAC.)

Before the 2002 conference Huete had spent several years repeatedly tinkering with the data and the mapping technique. "When you see something you are not expecting, you have to ask yourself, 'What are all the possibilities for a remote-sensing product going wrong?'" Among the possibilities are things in the atmosphere that keep the satellite from having a clear view of the surface. "We checked for aerosols [particles in the air, such as smoke from biomass burning] and clouds, which can potentially reduce the vegetation signal obtained by satellites. Someone suggested that maybe there was flooding on the forest floor during the wet season, so we looked at that. We looked how the vegetation maps changed if the light [hitting a particular patch of vegetation] was direct or diffuse. We just kept re-doing and re-doing the data products," he says. Each time they made a change, they wondered if the dry-season green-up would disappear. But with each refinement, it stayed. His confidence grew, but Huete still wasn't sure. Was this for real? Or was it just a sign he was still doing something wrong?



When satellite maps of Amazon vegetation showed unexpected seasonal patterns, Huete and his colleagues began to check out ways that remote-sensing observation can go wrong. This NASA satellite image acquired October 7, 2005, shows thin clouds and smoke partially obscuring the land surface. Huete's team checked their data for errors caused by clouds, smoke,

and changes in lighting to ensure their measurements were accurate. (Image by Robert Simmon, based on data from the Moderate Resolution Imaging Spectroradiometer.)

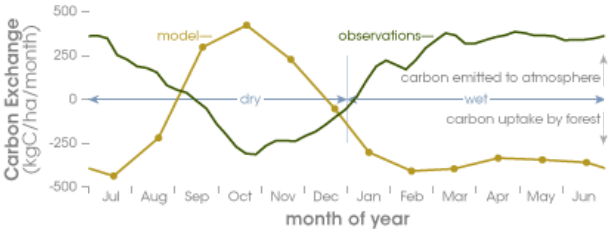
Abandoning His Doubts

In late 2002, Huete got just the sign he needed to put his doubts behind him. At a meeting of the American Geophysical Union, he saw a poster by ecologist Scott Saleska, then part of a research group led by Steven Wofsy of Harvard University, showing results of field studies at a location in the Tapajos National Forest in Brazil. The site was home to a research tower holding scientific instruments that Saleska and his colleagues had designed and operated as part of NASA's contribution to a Brazilian-led international research project called "LBA," short for the "Large-Scale Biosphere-Atmosphere Experiment in Amazonia."

At the Tapajós National Forest in Brazil, scientific instruments on a tall tower measure the rate at which the forest and the atmosphere around the tower exchange gases, such as carbon dioxide. In the image ecologist Scott Saleska scales the tower to check the equipment. (Photograph courtesy Alfredo Huete.)

Among the most important measurements collected on the 60-meter tower was the uptake and release of carbon dioxide by the forest. Vegetation takes in carbon during photosynthesis, but also releases it during respiration. Decomposition of dead trees and vegetation also releases carbon dioxide back into the atmosphere. Over the course of the project, they collected observations of the flux of carbon dioxide from the forest and compared those observations with the growth and death of trees surrounding the tower. The observations would reveal whether, overall, the area was a sink or a source of carbon.

After they had about two years of data, Saleska realized they were seeing something surprising. Although ecosystem models suggested that plants should be taking up less carbon dioxide in the dry season, when trees were expected to be water-stressed, what they saw was the opposite. Photosynthesis was greater during the dry season than during the wet season. "When I first plotted the comparison between our data and the models," said Saleska, "I thought for a minute that I had made a mistake by plotting the model predictions upside down."



When Saleska and his team first graphed the measurements of carbon dioxide exchange between the forest and the atmosphere at research sites in the Amazon, he thought he had done it backwards. Measurements (green line) were the opposite of predictions from ecosystem models (yellow). Models predicted that the forest would release carbon to the atmosphere (positive exchange) in the dry season (July-December) because water stress would slow growth. Instead, the trees consumed (negative exchange) several hundred kilograms of carbon per hectare per month during the dry season. (Graph by Robert Simmon, adapted from Saleska 2003.)

But results from a second flux tower nearby, operated by Saleska's colleagues, Michael Goulden from the University of California-Irvine, and Humberto da Rocha, from Brazil's University of Sao Paulo, showed exactly the same "backwards" pattern, boosting Saleska's confidence that the measured pattern at both towers was right. Saleska and his colleagues combined the results from the towers and presented them on a poster for the meeting.

"For several years, we had been seeing this dry-season green up [in the satellite data] and wondering whether it was real or not," says Huete. "But when I saw Scott's results, that the ground data at the tower sites showed the same thing as the satellite data, it really changed

everything for me. From that moment, I realized we could stop focusing on 'what's wrong' and instead focus on how to demonstrate that what we were seeing was real."

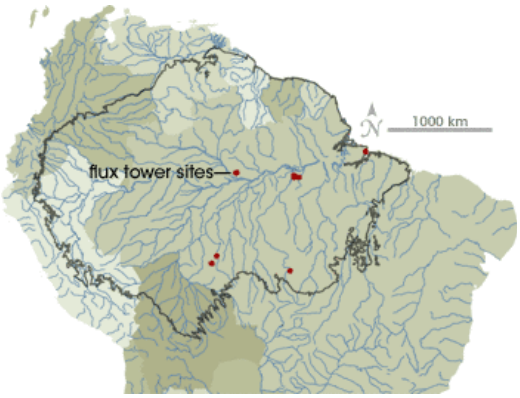
Getting further encouragement

As he began pulling the satellite data together and deciding the best way to demonstrate to other scientists that the dry-season green-up wasn't a mistake, Huete got some further encouragement that he was on the right track. In 2003, ecologist Rama Nemani of NASA Ames Research Center (a long-time colleague of Huete's) and other researchers published research that linked global changes in vegetation productivity between 1982 and 1999 to the three environmental conditions that most affect plant growth: precipitation, sunlight, and temperature. Using 20 years of climate data combined with satellite-based vegetation maps, the team developed a model that predicted which of the three factors most influenced the vegetation in different places on Earth.

Among the most interesting findings, says Nemani, was that the Amazon had experienced a large increase in productivity, apparently because of decreased cloud cover and increased sunlight. "Our analysis indicated that growth in the Amazon was light-limited, rather than water-limited," explains Nemani. Over the long-term, the Amazon had become more productive in response to greater sunlight. Huete and Nemani thought that the same phenomenon could be operating on the seasonal scale.

Detecting the Amazon's Seasonal Signal

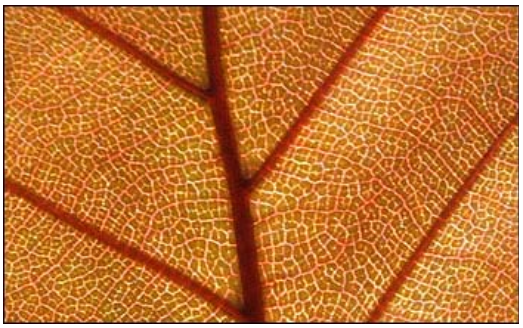
Trying to describe the big picture of seasonal dynamics across the entire Amazon Basin puts scientists in a catch-22. The forest is so big that satellites are the only way to make observations of the entire forest. But measurements collected from hundreds of kilometers above can sometimes be hard to tie to specific biological processes on the ground. On the other hand, a handful of ground stations scattered throughout 7.5 million square kilometers of forest can't tell the forest's entire story, either. To make a convincing case for an Amazon-wide, dry-season green-up, Huete knew that he would need both perspectives: space-based and ground-based.



Flux tower sites (red dots) provide on-the-ground evidence of forest processes, but are too widely scattered to describe seasonal changes across the whole Amazon. Satellite data cover the whole area, but can be hard to link to specific forest biology, like carbon uptake. Huete's team used both types of data to describe basin-wide seasonal changes in Amazon vegetation. (Map by Robert Simmon.)

For the satellite-view, Huete and his research team compiled 5 years of satellite vegetation data from the Moderate Resolution Imaging Spectroradiometer sensor on NASA's Terra satellite. The maps are based on the relative amounts of red and near-infrared light that the sensor detects over a location on Earth. Chlorophyll in

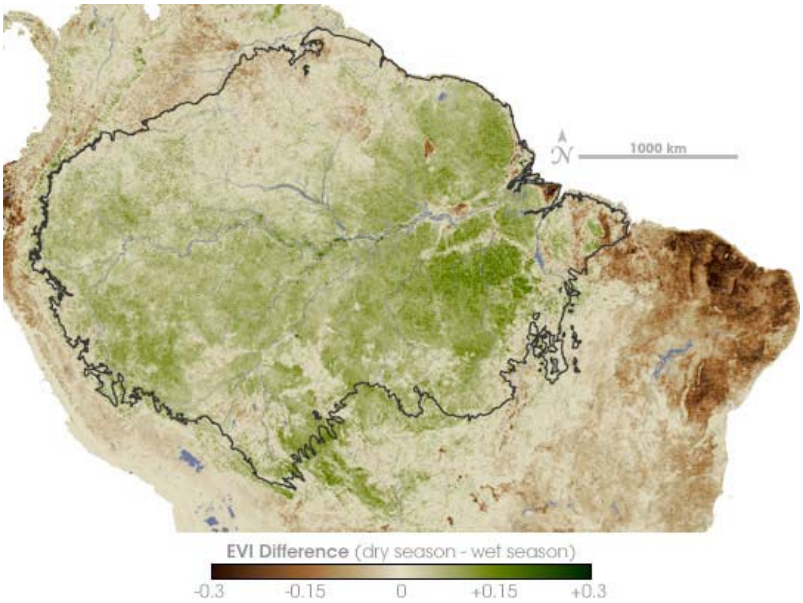
vegetation absorbs red light, while “scaffolding” (like cell walls) in the plants’ leaves reflect near-infrared. An area that reflects very little red light but a lot of near-infrared light back to space is likely covered in vegetation; scientists call this signal “greenness.” Greenness is an optical (light-based) way to measure forest productivity.



Leaves interact with different wavelengths of light in different ways. Chlorophyll and other light-harvesting pigments absorb red light very strongly, while a layer of spongy “scaffolding” tissue in leaves reflects near-infrared light. Land covered with vegetation will absorb red light and reflect near-infrared light. Remote-sensing scientists call this light signature greenness. (Photograph copyright M. J. Davidson.)

Like most tropical locations, the Amazon is very cloudy, especially in the rainy season. In the dry season, it can be pretty smoky from slash and burn deforestation and agricultural fires. The high humidity (water vapor) in the atmosphere can also interfere with measurements from satellites. To make sure their vegetation maps were free of clouds and other data contamination, Huete and his colleagues selected only the best-quality data from 2000-2005 and averaged them into a single “typical” Amazon year.

Once they had their example year, the team pored over the maps, looking at seasonal changes in greenness at three different scales: the whole Amazon, regional slices called transects, and small areas surrounding research towers like the one where Saleska worked. They subtracted wet season and dry season greenness values to identify seasonal patterns. At tower locations in undisturbed forests and sites that had been converted to pasture, Huete and Saleska made meticulous week-by-week comparisons of satellite greenness and ground-based measurements of carbon dioxide uptake.



After combining five years of satellite vegetation data, Huete and his team subtracted wet season measurements from dry season measurements. This map shows the results: vegetation index values were

At each scale, they saw the same pattern: undisturbed rainforests became “greener” and increased their photosynthesis throughout the dry season. In the regional transects, the scientists discovered that the longer the area’s dry season was, the greater the greening effect was. Even though it might seem like

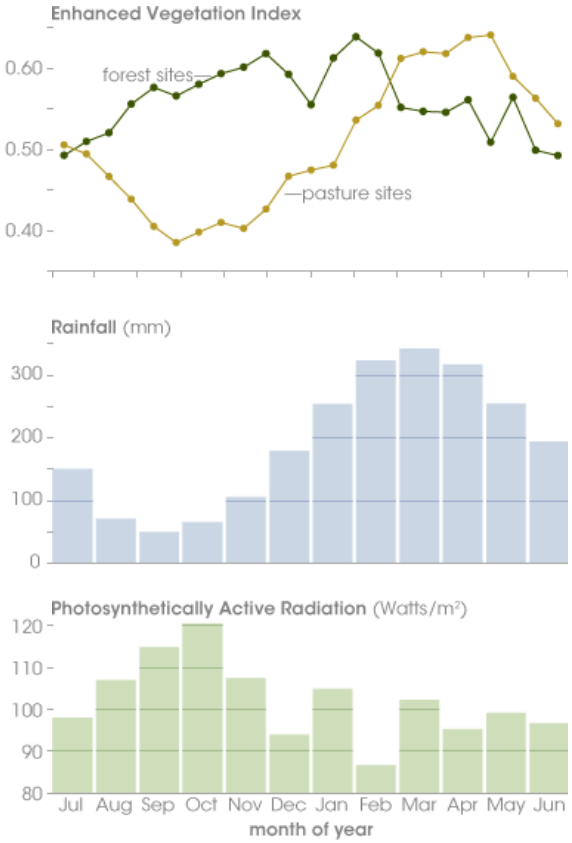
months with little or no rain ought to slow down the forests' ability to photosynthesize, Huete says the reverse appears true. "The dry season, with less clouds and higher sunlight, is actually the 'good' season."

▶ Forecasting the Future of the Amazon
◀ Abandoning His Doubts

higher (greener) during the dry season than the wet season in places where the Amazon forests were undisturbed. At pasture sites, such as in the southeastern Amazon, the vegetation was less productive (browner) during the dry season. Apparently, lack of sunlight in the wet season limits forest growth more than lack of water during the dry season. (Map by Robert Simmon, based on data from the University of Arizona Terrestrial Biophysics and Remote Sensing Lab.)

Forecasting the Future of the Amazon

As counterintuitive as a "good" dry season might seem, that response is perfectly in tune with research about the soil-water-tapping potential of mature rainforest trees. Since the early 1990s, field studies and soil-moisture modeling research have been accumulating evidence that in the undisturbed rainforest, roots extend as far as 20 meters (more than 60 feet) into the soil, where the wet-season rains are stored. Rather than being a time of stress, the normal dry season may be the forests' most productive time of year because the rain clouds clear up, and more sunlight reaches the forest.



Pastures cleared from rainforests show the opposite seasonal pattern from undisturbed rainforest. These graphs show the relationship between vegetation greenness (top), rainfall (middle), and sunlight (bottom). Greenness in forest areas (green line) increases when rainfall is low and sunlight is high (July-December). Greenness in pastures (gold line) increases in the rainy season (January-June). (Graphs by Robert Simmon, adapted from Huete 2006.)

But the dry-season green-up only happens in undisturbed forests, stresses Huete. At locations where the forest has been converted to pasture or farmland, the dry season has the more intuitive effect: the vegetation "browns down" in response to decreased soil moisture. Once the deep roots of the mature trees are lost, the access to the water stored deep in the soil is lost as well.

Because of the Amazon's size and productivity, small changes in the carbon stored there can produce a global effect. Many ecological models are based on the idea that the dry season is a time of stress. Some models predict that future warming and drying of Earth's climate may cause the rainforest ecosystem to collapse, turning the area from lush forest (top) into tropical savanna (below). Such a transformation would dramatically change the Amazon's role in the global carbon cycle. The discovery of a dry-season green-up indicates that many questions remain about how the Amazon will respond to climate change. (Rainforest photograph copyright Brant Olson, pasture photograph copyright Lady Drid.)

"Some current ecological models of the Amazon actually have the Amazon getting browner during the dry season," explains Huete. If the seasonal cycle of green-up and photosynthesis in a model is wrong, the ability to predict uptake and release of carbon dioxide, water availability, and fire risk would probably be off as well.

Among the key implications, explains Saleska, is the fate of the Amazon itself. In most models that link simulations of global climate to vegetation dynamics, the Amazon has a big influence on carbon because even small changes in the great stores of carbon in the vast Amazon forests can have significant impacts at the global scale. "But what we are learning is that Amazon is highly sensitive to hydrological change," he says. "When the modelers couple their climate models to ecosystem models of the Amazon and run them out over the next century, some models predict that Earth's warming climate will cause the whole Amazon ecosystem to collapse, to become a savanna."

Instead of a dense forest richly layered with trees, shrubs, plants, and vines, the whole area could instead be covered by grass and scattered trees. In addition to the radical transformation of the ecosystem and loss of biodiversity, "there would be significant global impacts of that collapse," explains Saleska. After taking into account the current rates of deforestation, scientists think the Amazon region may be neutral with respect to carbon losses and gains. But if savanna replaced the rainforest, says Saleska, "the whole area would switch from being close to neutral on average to being a big source of carbon."

"But if these models are getting the seasonality wrong, then the impacts [of climate change] may not be what we expect," he continues. Predictions of ecosystem collapse are based on the idea that the dry season is a time of stress and declining greenness. If that isn't true, then perhaps the Amazon will be more resilient than the models predict. On the other hand, a typical dry season isn't the same as a lengthy El Niño-induced drought. Previous studies, including a drought-simulation experiment conducted during LBA, indicate that the more severe, extended declines in rainfall that can happen during strong El Niño events do produce stress in the forest, especially fragmented or damaged areas. With forest disturbance on the rise and predictions by some climate models that El Niño events may increase as climate warms, the fate of the Amazon is unclear.

In the near future, Saleska and Huete will be working together to do a synthesis of all the available LBA tower observations with the satellite data to come up with a basin-wide estimate for the flux of carbon in the Amazon. In the meantime, says Saleska, everyone is keeping their eyes out for the next strong El Nino because observations collected during the event could provide the next key piece of the puzzle of how the Amazon responds to large-scale climate variation and change. Knowing the Amazon's baseline seasonal response should help scientists judge when and how future climate events may disturb the balance of such an important and sensitive ecosystem.

References:

Huete, A.R., Didan, K., Shimabukuro, Y.E., Ratana, P., Saleska, S. R., Hutyra, L.R., Yang, W., Nemani, R.R., and Myneni, R.(2006) Amazon rainforests green-up with sunlight in dry season. *Geophysical Research Letters,* 33, L06405, doi:10.1029/2005GL025583.

Saleska, S.R., Miller, S.D., Matross, D.M., Goulden, M.L. Wofsy, S.C., da Rocha, H.R., de Camargo, P.B. Crill, P., Daube, B.C., de Freitas, H.C., Hutyra, L., Keller, M., Kirchhoff, V., Menton, M. Munger, J.W., Hammond Pyle, E. Rice, A.H., Silva, H. (2003) Carbon in Amazon Forests: Unexpected Seasonal Fluxes and Disturbance-Induced Losses. *Science* 302, 1554–1557.

Links:

Introduction to the Large-scale Bisophere-Atmosphere Experiment in Amazonia

LBA-ECO Project Website.

Alfredo Huete's Webpage. Department of Soil, Water, and Environmental Science at the University of Arizona.

Defying Dry: Amazon Greener in Dry Season than Wet

by Rebecca Lindsey • design by Robert Simmon June 30, 2006

by Holli Riebeek· design by Robert Simmon· March 13, 2006

When Alfredo Huete saw Scott Saleska's poster presentation at a meeting of the American Geophysical Union in 2002, he felt like he had been unleashed. Several years before, Huete had been sponsored by NASA to develop techniques for mapping global vegetation using data from a new sensor planned for two of the space agency's upcoming Earth-observing satellite missions. For several years after Terra, the first satellite, launched in 1999, the University of Arizona remote-sensing ecologist had been worrying over the data processing and mapping technique he and his team had proposed.

caption (Photograph copyright Naadir Jeewa)

For nearly two decades, scientists had been mapping global vegetation patterns using a vegetation scale, or index, based on data from a series of satellite sensors operated by the National Oceanic and Atmospheric Administration. Although the new NASA sensors drew on and even surpassed the capabilities of the previous sensors, they weren't identical to what had come before. Huete had to deal with a new kind of satellite sensor, a new method for producing the vegetation maps—and the awareness that he was making a product that would go out into a global research community with NASA's name on it. "I felt a lot of pressure," Huete says.

Amazonia covers most of tropical South America east of the Andes Mountains. Primarily rainforest, the region includes some of the densest vegetation and greatest biodiversity on Earth. This map shows enhanced vegetation index, a measure of plant vigor, in South America. Satellite measurements of EVI revealed that the Amazon is greener in the dry season than during the rainy season, contradicting conventional wisdom. (Map by Robert Simmon)

As they were developing and testing their technique, Huete and his team frequently checked that the maps matched real-world seasonal changes in vegetation in different ecosystems, from African savannas to eastern North American forests. Although their maps captured the expected seasonal changes in most areas, one area bothered Huete: the Amazon. As data from Terra began accumulating, he noticed something peculiar: the Amazon rainforest looked greener to the satellite in the forest's dry season than it did during the rainy season. Huete knew that parts of the forest go several months with little or no rain. How could the forest be thriving during those times of seasonal drought?

graph of EVI over time

caption (Graph by Robert Simmon and Jesse Allen)

Huete had spent several years repeatedly tinkering with the data and the mapping technique. "When you see something you are not expecting, you have to ask yourself, 'What are all the possibilities for a remote-sensing product going wrong?'" Among the possibilities are things in the atmosphere that keep the satellite from having a clear view of the surface. "We checked for aerosols [particles in the air, such as smoke from biomass burning] and clouds, which can potentially reduce the vegetation signal obtained by satellites. Someone suggested that maybe there was flooding on the forest floor during the wet season, so we looked at

that. We looked how the vegetation maps changed if the light [hitting a particular patch of vegetation] was direct or diffuse. We just kept re-doing and re-doing the data products," he says. Each time they made a change, they wondered if the dry-season green-up would disappear. But with each refinement, it stayed. His confidence grew, but Huete still wasn't sure. Was this for real? Or was it just a sign he was still doing something wrong?