WATER IN PLAIN SIGHT

HOPE FOR A THIRSTY WORLD

BUILDING SOIL, RESTORING LAND, AND WORKING WITH THE WATER CYCLE FOR A COOLER, WETTER PLANET

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Missing the Water for the Trees

How Plants Make Water

Rain rain go away, let's chop a forest down today?

—Joanne Nova of Western Australia, 2013

By this time the 1910 oaks were ten years old and taller than both him and me. . . . Going back down through the village I saw there was water flowing in streams that had been dry as long as anyone can remember. As chain reactions go, this was the most remarkable one I'd ever seen.

—"The Man Who Planted Trees,"
a fable by Jean Giono, 1953

ONE OF THE WORLD'S MOST BELOVED AND ROMANTIC cities has a restoration narrative at its core. Rio de Janeiro's story came to me courtesy of Tom Goreau, a scientist with numerous overlapping specialties (his discipline is biogeochemistry) who has spent much time doing research in the Amazon. This is what he shared:

When European explorers encountered the Guanabara Bay in the early 1500s, the surrounding mountains were covered with forests. Over the centuries the trees were steadily cut down for building and firewood, and then for sugar and ultimately coffee plantations, or *fazendas.* The city's iconic backdrop, those looming, high, bare mountains, is the result of this loss of cover. With the trees stripped and gone, soil from the slopes washed away, leaving hard, naked bedrock. Meanwhile, the city's population increased rapidly and many grew wealthy on the coffee trade. (Incidentally, coffee isn't native to Brazil but was introduced in the early 1700s from nearby French Guiana, where it was being cultivated.) It was only a matter of time before the land's fertility crashed.[1]

By the 1800s, rainfall decreased and the rivers dried up. Once-abundant springs were hardly a trickle beyond the rainy season. The city, now the colonial capital, ran out of water and people were desperate. Many fled to the countryside. People saw that their water troubles were linked to deforestation, because when there were forests there had been water. The king, Dom Pedro II, decided something needed to be done, and charged a military officer, Major Manuel Gomes Archer, with reforesting the entire area. Archer selected a variety of tree species, mostly native to the Atlantic Forest but a few exotics as well, and employed a group of six slaves to plant them. The slaves—whose names are lost to history—devoted several decades to this task, climbing and carrying saplings up steep, sometimes near-vertical inclines, and planting more than 75,000 trees. In time the forest did come back, along with the springs and rivers, and the water supply was stabilized. The Tijuca Forest, declared a national park in the 1960s, is considered the world's largest urban forest.

(Actually, my husband's hometown, Johannesburg, also lays claim to this title. Beginning in the late 1800s the planting of some 10 million trees in the city was apparently driven by the need to prop up mine tunnels. And real estate appeal: the pleasant neighborhoods north of downtown—nicely gardened and swimming-pooled, redolent of bird song—are not called the "leafy suburbs" for nothing.)

Antonio Donato Nobre is senior scientist at Brazil's National Institute for Amazonian Research in Manaus, smack in the center of the Amazon basin, where he has spent twenty years of his career. For the last twelve years he has also been a visiting scientist at Brazil's National Institute for Space Research in São José dos Campos, a small city outside São Paulo along the highway to Rio. He's from a family of scientists—two brothers, Carlos and Paulo, are both highly respected climatologists—and the account of the revived Tijuca Forest is part of his cultural, intellectual and even spiritual DNA. "I've used this story many times," he tells me over Skype. "It's a useful symbol of the incredible capacity of nature. Before the replanting there were problems with water quantity as well as quality, because of erosion from the farms. King Dom Pedro II was very connected to science. He used to travel all over the world to see science fairs. He had a friendship with Goethe. He brought over botanists from France."

Nobre says he's amused that the restituted Floresta da Tijuca is sometimes described as "pristine" Atlantic Forest, and that many local people assume the trees have always been there. "As you walk there, you still find old coffee plants that have been abandoned, as well as old fruit trees. That's proof that this area was recovered. Today Rio cannot rely on this water for its supply. But the creeks that come from these mountains are pure."

The water saga that occupies Antonio Nobre's mind today is less lofty and affirming: that is, the water crisis in São Paulo, the most populous city in the Americas. In early 2015, after consecutive years of heat and low rainfall, the Cantareira network of reservoirs that provides water to nearly half of the megacity's 20 million residents languished at a mere 5 percent of capacity.[2] Rumors of strict mandatory rationing spread as experts gave estimates of how many weeks the water supply was expected to hold out . . . fewer than ten. Some apartment-dwellers saw their water shut off without warning—for three, four, five days—while others were assigned hours for when they could run the tap. Locals have responded in varied ways: hoarding water; setting up water delivery services by bicycle; digging private wells (which may or may not meet code requirements); or leaving the area altogether, a historical echo of Rio's nineteenth-century water refugees prior to the Tijuca Forest's restoration.[3] Commentators have noted the irony that Brazil, which has been called "the Saudi Arabia of water," is confronting such a dire shortfall.

"São Paulo is following on California's footsteps," says Nobre. "We've had four years of drying up and then in 2014 a massive drought. People are anxious because it's different from some places like the southwest U.S. that have been dealing with aridity for a long time. This area has been green forever. There's always been abundant rainfall. But for most of 2014 people were looking to the horizon and seeing the same atmosphere as you'd see in the Sahara: the same layer of dust and blue sky and heat. There's no moisture and people are scared, shaking in their boots. At the same time the government has done almost nothing, as if the next wet season would save us."

For Antonio Nobre, like most Brazilians, the crisis has been a shock. He's spent his life in lush, green, water-rich settings: a childhood in the Atlantic Forest near São Paulo, not far from where he now lives; graduate studies at the wooded University of New Hampshire; decades of research in the Amazon jungle. These days, however, he's been inundated with the drought. His wife, Adriana Cuartas, is a hydrologist who works for a national center on disaster preparedness and response. Her current task is monitoring the status of the reservoirs. Each evening she would return home, sigh, and offer a somber update on the dwindling basins. For months it was dry news every day. Should Nobre choose to seek refuge in the shower—a favorite place to think, about water shortages among other matters—he'd face the indignity of his nine-year-old daughter, Isabella, scolding him and saying, "Dad, you're not saving water!" (Nothing like parental guilt: he's learned to put water-capturing receptacles in the shower.)

Not that a problem with water was a surprise to him. Indeed, Nobre has had the uncanny experience of seeing his own scientific predictions materialize right before his eyes. Late in 2014, just as the drought's severity was registering among politicians and the public, he published a scientific report entitled "The Future Climate of Amazonia,"[4] a work that reviewed more than 200 scientific articles including material from a multiyear international research effort called the Large-Scale Biosphere-Atmosphere Experiment in Amazonia (LBA).[5] From 1998 to 2008 this project, led by Brazil's scientific community, amassed an extraordinary amount of data on the processes and exchanges that characterize the rainforest ecosystem. Among the LBA's objectives was assessing "the interaction of humans with the landscape."

Nobre's paper emphasizes the role that the world's largest extant rainforest plays in helping to create and sustain a benign, "friendly" climate across the entire continent. In clear, accessible language it also conveys the grim warning that chain sawing, bulldozing, burning and otherwise trashing the rainforest stands to wreak havoc on the temperature and rainfall patterns that all—people, nations and natural systems alike—depend upon.

"I did not have a plan to publish this report during the drought," he says. "I was describing how powerful the Amazon rainforest is when it's intact, and its importance to climate throughout the region. Then as I was writing the report the drought imploded." The Amazonia report makes the case that the water that nourishes South America's landscapes turns on the fate of trees.

Unlike the story of the Tijuca Forest's restoration, says Nobre, in this instance it's the loss of trees that's having an impact.

The notion that there's a connection between forests and water sufficiency is not new. Plato and Aristotle wrote about how deforestation leads to the loss of water resources. The eighteenth- and nineteenth-century adventurer and naturalist Baron Alexander von Humboldt wrote: "By felling the trees which cover the tops and sides of mountains, men in all climates seem to bring upon future generations two calamities at once; want of fuel and a scarcity of water."[6] In his 1864 book *Man and Nature* (original title: *Man the Disturber of Nature's Harmonies*), George Perkins Marsh catalogs numerous examples of deforestation and its denouement from his diplomatic and literary travels. He wrote: "When the forest is gone, the great reservoir of moisture stored up in its vegetable mould [soil or humus] is evaporated, and returns only in deluges of rain to wash away the parched dust into which that mould has been converted. The well-wooded and humid hills are turned to ridges of dry rock."[7]

Popular histories like Jared Diamond's *Collapse* and David Montgomery's *Dirt: The Erosion of Civilizations* are full of cautionary tales of societies—the Mayans, Pacific Islanders, cases in the French Alps—that squandered their tree cover, resulting in catastrophic flooding and drought.

In order to find an example of how forest loss messes with water I don't even have to leave home. A recent copy of *Ripples,* the newsletter of the Vermont Agency of Natural Resources, informs us that European settlers dispensed with more than half the state's forest cover by the close of the nineteenth century. This was the result: "Cleared land froze more deeply in winter and thawed more quickly in warm months. While spring brought floods, the hot summer months left streams and rivers dry. Vermont historian Samuel Williams noted in 1794 that cleared land 'became warm and dry, while streams and brooks no longer supplied water.' Soil erosion contributed to the situation of streams, ponds and lakes, and gave rise to changes in fish and animal populations."[8]

As I read this it occurred to me that Vermont's "mud season," the postsnow March–April stretch that is every bit as dreary and messy as it sounds, is no foreordained inevitability. Rather, it stems from our predecessors' zealousness about dispatching old-growth native trees so that they could make room for sheep.

That forests are important to the water cycle makes logical sense. Trees stabilize the soil, which guards against erosion. The presence of trees therefore enhances soil's ability to hold rainfall rather than letting the water stream away, carrying off precious organic matter. A tree's canopy intercepts rain so that the water descends gently to the ground, not with the kind of pounding bombardment that leaves craters in bare soil or overwhelms the land's ability to absorb it.

At the Urban Soil Summit in Los Angeles, Andy Lipkis of TreePeople pointed to the quiet, unheralded absorption that trees perform when it rains: the root system of a mature tree can retain tens of thousands of gallons of rainwater—water that in urban areas would otherwise course away onto asphalt and into gutters and eventually merge with the waste stream.[9]

Lipkis shares this information in presentations, he says, "to create the model of how urban trees could and should perform if we properly design urban spaces to function as, and biomimic, forest watersheds. It is intended to create a context for how to think about designing or retrofitting for resilience. Urban trees perform some of these functions, but they barely reach their potential because for the most part, their connection to the watershed is nearly completely severed by urbanization . . . streets, sidewalks, gutters, which convey water off properties and into the storm drain system. Soil is compacted or covered with impermeable surfaces. If the soil around a tree is properly managed, then yes, the capacity of the tree to provide those water supply, quality, carbon storage, habitat and flood protection [attributes] would be greatly enhanced and, depending on tree size and other conditions, could grow to tens of thousands of gallons."

In addition, the shade of a tree canopy cools the ground so that moisture is less prone to evaporate, thus keeping water in the system. Trees recycle oxygen and water vapor, which improves the quality of the air and lends it a soft humidity. We all know how nice it is to be near trees. In Japan there's a healing practice called *Shinrin Yoku,* translated as "forest bathing," which research has found lowers stress and boosts immunity.[10]

Bill Mollison, the biologist and teacher considered the "father of permaculture," has a series of videos in which he speaks extemporaneously about trees and how they function in a landscape. He says that a tree is 93 to 98 percent water. "A tree stands there as a barrel of water," he says, and likens a forest to a kind of lake. To fully "wet" a tree, a rain shower may have to cover forty acres worth of leaf, he says. Most precipitation is intercepted by trees, which redirect the flow of rain. This "redistributes the water very differently from if it fell on a field." The tree steers the water so as to "fit its own needs. Each tree does something very different."[11]

The water that filters through the canopy, the throughfall, is distinct from ordinary rain, says Mollison: "It's the tree's bathwater. It's a much richer substance than rain." This arboreal elixir has a different ionic makeup, contains trace elements, and is less acidic than precipitated water, he says, noting, "The most nutritious pasture is near trees."

Trees in the landscape also slow the water cycle. Alice Outwater writes: "A single water molecule making its way through a stream-and-forest ecosystem is on a biological Ferris wheel. A raindrop may hit a leaf, trickle down to the bark of a branch, evaporate to come down again as rain. . . . Snowflakes that fall to the forest floor pile up in a blanket tucked around the trees, shaded from the sun."[12]

Trees contribute to environmental and human well-being in all sorts of ways: storing carbon, bestowing shade, sheltering species from birds to leopards to lemurs, luring leaf-peeping tourists to Vermont in October. Lipkis cites research from the city of Melbourne, Australia, that found tree canopy cover of 40 percent cooled an area by nine degrees. Not only does this make life more pleasant—it can apparently get kind of sticky in Melbourne—but it saves lives. "As extreme heat events have been occurring in Australia, temperatures in some of their major cities have risen to 115 degrees Fahrenheit, and above, causing people to die after three days of constant high heat without relief," he wrote to me. "Public health researchers determined that lowering peak temperatures by 4 degrees centigrade, roughly 7 degrees Fahrenheit, would be enough to save people, and have stated that people should live in neighborhoods with both dense tree canopy cover AND available soil moisture, to enable evaporative cooling. To adapt to various threats posed by climate change, City of Melbourne officials have set and begun implementing a target of 40 percent tree canopy cover over the city to achieve the seven-degree peak heat reduction."[13]

The ecological benefits trees impart are in bureaucratic terms known collectively as "ecosystem services." Such attributes make rain more effective, stabilize and enrich soil, and shield the ground from excess evaporation loss. These are functions we all know or intuit. In his report, however, Nobre says trees' importance to hydrological processes transcends water's earthward flows—he makes the case that forests are crucial to the *production of rain.* And that without sufficient forest cover, the rains of an entire region could fail.

"The Future Climate of Amazonia" is a formidable document. Reading it evokes at once awe for the massive force embodied in the billions of trees that compose the Amazon, and a chill upon acknowledging its vulnerability. Nobre describes how the Amazon rainforest hydrates a good chunk of our hemisphere and acts as an "environmental regulation machine." He refers to stretches of dense, extensive forest as a "green ocean" whose moisture, enormity, and ongoing exchange with air and wind mirrors that of its blue marine twin. He notes the clouds that hover over the Amazon rainforest resemble those that sail above the sea; like the atmosphere over the vast expanse of ocean, the air above Amazonia is clean and free of dust because it's continually cleansed and scrubbed by rain. The very term *green ocean* suggests the waves of humidity that move over and across the rainforest, a sea of vapor that supports stunning plant and animal diversity.

To really grapple with the forest-rain dynamics Nobre is getting at, we need to explore the concept of transpiration.

Most basically, transpiration is the upward movement of moisture through living plants. A plant emits water vapor to the atmosphere through its stomata, small openings on the underside of the leaves (in grasses, on the blades). You can think of this as the plant "breathing," or, more precisely, "sweating." As stomata are valves that open and close, this enables the plant to release or retain moisture, and to regulate its own temperature and that of the ground. Transpiration is a cooling mechanism; it is a means of dissipating solar heat. Without the presence of plants, sunlight would beam down directly on the landscape.

Jan Pokorný, a Czech botanist, has put together a short pamphlet entitled *What Can a Tree Do?* The piece enumerates the ecosystem services a tree provides, but is couched in the language of advertising. (As in: "The device should work in complete silence and produce no exhausts or waste. All the elements of the device are bio-degradable.")

Pokorný's tree "sales pitch" explains the extent to which transpiration consumes and transforms energy from the sun, which makes trees the world's most perfect air conditioners. Take an ordinary tree in full leaf whose crown spans five meters, or about sixteen and a half feet, in diameter. On a sunny day, our nice-sized tree would have at least 150 kilowatt-hours of solar energy shining on it. Given sufficient water, over the course of the day the tree would transpire upward of one hundred liters (more than twenty-six gallons) of water. (Pokorný says this represents three times the cooling power of an air-conditioning system in a five-star hotel room.)

The energy consumed by transpiration is now embodied in the vaporized water in the form of "latent heat"—heat potential. This is opposed to "sensible heat," or heat you can feel. (For sensible heat, think walking barefoot on asphalt midday in August.) Even in the heat of summer, a forest is pleasantly cool. In part this is due to shade, but also because the trees are transpiring—moving solar heat into a state of suspension. The heat held in abeyance will be released upon condensation, at which point the vapor turns to liquid.

The cycling of moisture via trees is as constant as it is invisible, a parallel universe of vapor, an ethereal realm. In *The Tree: A Natural History of What Trees Are, How They Live, and Why They Matter,* British biologist and author Colin Tudge brings this liquid vision to light: "It would be wonderful with X-ray eyes to see a forest without the timber. It would be a colony of ghosts, each tree a spectral sheath of rising water."[14]

In a verdant tropical forest like Amazonia, the carbon, nutrient and water cycles are accelerated: the soil-plant-sky circuit runs quickly. The furious expression of botanic energy provoked terror among the Spanish conquistadores, who called the jungle the Green Hell, *el Inferno Verde.* The rate of transpiration in the Amazon Basin is such that individual trees are veritable fountains, transferring large quantities of water from the ground and into the air like a natural spring. Nobre writes that on a given day, a single large tree in the rainforest "can pump from the soil and transpire over a thousand liters of water." As permaculture pioneer Bill Mollison puts it, "The tree has an intimate connection with rain. There's a constant exchange between the tree and the cloud."[15]

Given the 4 billion or so trees in the rainforest, Nobre writes, an estimated "twenty billion tons of water are transpired per day by all the trees in the Amazon basin. As a whole, these trees—those benevolent silent green structures of nature—act like geysers and spout a vertical river of vapor into the air that is even greater than the Amazon River."[16] Forests are such prodigious evaporators because of the intricate layering and overlapping of leaves; this creates abundant surface area for vapor exchange.

Whenever we do our calculus of water resources and look at the balance sheet, we often neglect to consider plants. Transpiration may be considered incidental to water fluxes, and often referred to as a loss of plant moisture. However, it plays a huge role in the movement of moisture into the atmosphere. In research published in *Nature* in 2013, Scott Jasechko and colleagues used isotope analysis to determine the sources of atmospheric moisture. According to the study, transpiration from vegetation accounts for between 80 and 90 percent of all moisture that ascends to the atmosphere from the continents; only slightly more than 10 percent derives from simple evaporation from land or bodies of water without plant intermediaries.[17]

We regard plants mainly as *recipients* of water—but in fact they're also key determinants of *where water goes* and *what it does.* In other words, vegetation—particularly trees, which evaporate more moisture than grasses and shrubby plants—helps drive weather and climate.

This unseen evaporated moisture is not simply lofting into the air and staying put; it's moving horizontally, along currents buoyed by wind. The Amazonia report presents the concept of "aerial rivers" whereby moisture, driven by evaporation, is transported from humid forested areas to other places where it falls as rain. Nobre notes a recent climatology review that identified "aerial lakes" that store water in the atmosphere as a kind of precipitation reserve.[18] Research in the Amazon region used isotope tracers to demonstrate that water from the forest was "exported" to other parts of the continent. The Amazon River ranks first among the world's rivers in how much water it carries to the sea: 200 million liters per second, or 17 billion tons daily. And yet, writes Nobre, the moisture flow that passes through the rainforest, the aerial river in the lower atmosphere that soars undetected above the mighty river we can see, actually exceeds this.

Nobre says the floating river phenomenon helps explain the "mystery" of why the plains east of the Andes mountain range receive plenty of rain. By contrast, other regions at that latitude—the Atacama Desert (the western edge of the Andes, deemed the world's driest place), the Kalahari, Namibia, the arid expanse of western and south Australia—are desert or savanna. He calls this the "lucky quadrangle," the chunk of South America that generates 70 percent of the continent's GNP. He writes: "The Amazon rainforest not only keeps the air moist for its own purposes, but also exports water vapor via aerial rivers, which carry the water that will produce the abundant rainfall that irrigates distant regions during the summer months."

Though it straddles the equator, the Amazon forest is always comfortably cool. Tom Goreau conducted research during the 1980s in which he compared the temperature in virgin Amazonian jungle with a nearby area that was clear-cut and overgrown with weeds. In the forest, the temperature from the hottest to coolest times of day remained within 1.5 degrees Celsius and was always "delightful." Where trees had been stripped bare, the temperature spanned 15 degrees Celsius and it got much hotter.[19]

The ambient cool that suffuses the rainforest is the product of countless trees transpiring. It can only be enjoyed thanks to much botanical labor—the energy-intensive work of converting liquid water to gaseous vapor. In order to understand just how much energy this requires, Nobre invites us to envision the rainforest's daily evaporation yield poured into an impossibly large imaginary kettle. "If you put this 20 billion tons of water to boil, you would need 50 thousand Itaipus," he says, referring to the hydroelectric dam between Brazil and Paraguay whose power-generating capacity is second only to China's Three Gorges Dam. "And the Amazon does this for free."

Later in the document Nobre explores another paradox: why is the rainforest so rainy? To form rain droplets, water vapor molecules need some kind of particle to coalesce around: minute flecks of dust, pollen, salts or soot, bits of debris that would serve as condensation nuclei and promote the formation of clouds. Precipitation certainly happens: enough, he writes, to prompt the joke that the Amazon has two seasons, "wet" and "wetter." So something is clearly seeding the rain. And yet, as we've seen, the air in the lower atmosphere—the troposphere—above the forest is nearly empty of dusts and other aerosols. This also is true of the air above the ocean, which helps explain why many maritime stretches receive little rain. However, the Amazon region gets lots of rain—in some places, upward of nine feet a year.

How can this occur without cloud condensation aerosols?

Again, it has to do with trees. Nobre says tree leaves emit carbon-based gases called biogenic volatile organic compounds. He calls these "scents of the forest" (or, inspired by the animated films his two daughters watch, "pixie dust"). These tiny iotas of matter—"a magical powder produced by life"—induce rainforest rain, and therefore solve the lack-of-condensation-nuclei puzzle. A research team with the Max Planck Institute studied how these "scents" function in the humid rainforest air. The group found that when exposed to solar radiation, these aromatic specks "oxidize and precipitate to form very fine dust particles with an affinity for water. . . . Poetically speaking, this is the *pixie dust* that magically appears in the moisture-laden air, and causes rain to bucket down from low clouds, i.e., the watering cans of the Garden of Eden."[20]

There's only one problem: some 300,000 square miles of Amazonia has been deforested, the size equivalent of two Germanys or two Japans. Nobre converts this to units Brazilian readers would understand: 184 million soccer fields, or nearly one soccer field's worth of rainforest lost for each person living in Brazil.

Today, he writes, the "wet or wetter" description of seasons no longer holds: "Now, there is a pronounced dry season, and the duration of the wet season diminishes progressively."

Can we blame the loss of trees?

I first learned of transpiration as a climate driver from a free booklet on the web called *The New Water Paradigm: Water for the Recovery of the Climate,* written by a group of Eastern European scientists, including Jan Pokorný and Michal Kravčík. A hydrologist based in Slovakia, Kravčík was awarded the 1999 Goldman Environmental Prize for providing alternatives to large dam projects that not only would have been ecologically damaging, but also would have destroyed four 700-year-old villages. Their publication completely upended my thinking about water and climate. In short, it fairly blew my mind. Much of the book focuses on the importance of keeping water on the land—the unheralded role of "green water." What truly grabbed me, however, was the extent to which the water cycle interacts with the energy cycle: how vapor conveys heat, alternately storing thermal energy (via evaporation) and releasing it (via condensation) as it circulates.

This offered a glimpse into the dynamism of air, that which we breathe and move through, a kind of mirror ocean riding ambient tides. Day and night, wafts of vapor wheel around the atmosphere, transforming conditions on the ground despite its weightlessness and invisibility. This moisture is, inevitably, an essential part of what creates and modifies our climate. Yet this humidity is not simply recycling moisture in a tidy, predictable way. Rather, it's diffuse and capricious, on the move, and determined by numerous other equally mysterious factors, including the presence and vigor of vegetation.

When we hear about links between water and climate, the connection tends to go in one direction: the impact that climate change may have on water sources. This is where we end up tying ourselves into knots when we say this drought or that storm may or may not be indicative of global warming. Because no single correlation can be proved, the conversation never gets beyond the chattering of talking heads.

What rarely gets airtime, however, is the extent to which *water influences climate.* In preceding chapters, we've explored some of the routes by which water has an impact on climate; in chapter 3, I noted Australian scientist Walter Jehne's statement that "over 90 percent of the global heat dynamics and balance is governed by a range of water-based processes." (Jehne says this creates the opportunity to employ cooling aspects of the water cycle as we strive to reduce CO_2 levels.) Also, we've seen how desertification can be regarded as both a consequence and a cause of climate change—that the inability to maintain ground moisture leads to a vicious cycle of unproductive land, biodiversity loss and soil carbon oxidizing to become CO_2. Plus the opposite: restoring the water cycle supports biodiversity, which, in turn, helps to bring the carbon cycle into balance. As our Amazonian adventure has taught us, plants, notably trees, have a huge influence on water. And yet, Jan Pokorný tells me, "Our understanding of the role of water and plants in landscape functioning is the equivalent of medicine before Pasteur."

Douglas Sheil is an ecologist who has been exploring the connection between forests and rainfall. An Irish fellow with a doctorate in tropical ecology from Oxford University, Sheil teaches at the Norwegian University of Life Sciences near Oslo. He also takes long research jaunts to forests in places like Indonesia, Borneo and Uganda. He helped establish the Institute of Tropical Forest Conservation at the Bwindi Impenetrable National Park, part of an extensive primeval forest that's home to the critically endangered mountain gorilla, among hundreds of other indigenous species: mammal, bird, plant and butterfly.

Sheil works with local communities, people who continually move between crop fields and forests—areas that are respectively partially and fully wooded. "The impression among local people is that the forests attract the rain—that there's no question about that," he tells me. "When you talk to climate scientists, however, there's no recognition. If there's a forest it would be because there was water first and the forests came later."

In 2014 Sheil published an article entitled "How Plants Water Our Planet." The opening sentence is a zinger: "Most life on land depends on water from rain, but much of the rain on land may also depend on life." This isn't how we generally think about it. As if anticipating skepticism from a frowning reader, he continues: "Recent studies indicate that vegetation, especially tree cover, influences rain and rainfall patterns to a greater extent than is generally assumed."

Sheil notes that while the forces that govern rainfall over land remain stubbornly elusive to scientists—*unresolved processes* is the term often used—new research sheds light on the role of plants. He refers to the 2013 study by Jasechko and colleagues that found between 80 and 90 percent of continental atmospheric moisture comes from plants. This is extraordinary, he says, considering (1) previous estimates ranged from 20 to 60 percent, and (2) this includes evaporation from ground surfaces and bodies of water, such as lakes and rivers, which many would assume were key sources of moisture.[21]

In another study in *Nature,* published in 2012, Dominick Spracklen of Leeds University and colleagues used several streams of data including satellite observations to monitor the movement of air and rain over the tropics. The authors found that winds that moved across forested areas tended to generate more than twice as much rain when compared with winds that traveled over open areas, including land cleared for farming.[22]

Is word getting around that not only do plants need water, they also give us water? A 2015 news feature from the American Geophysical Union has a headline that plays on the link between plants, condensation aerosols and rain, and challenges the conventional wisdom: "April Flowers Bring May Showers?"[23]

Sheil stresses the role that trees in particular play in moving moisture around the globe. He writes: "Leafy tree canopies produce flows of water vapour that, per unit land area, are typically more than ten times greater than from herbaceous vegetation." He notes that even when the soil is dry, a tree's deep roots draw on moisture so as to also provide water to nearby shallow-rooted plants. And that for short time periods trees can transpire more water than they actually pull from the ground: they rely on moisture stored in their trunks, then replenish by taking in water as it condenses in cooler nighttime air. He adds that aerosol concentrations tend to be higher over forests than grasslands. (To paraphrase Jan Pokorný's *What Can a Tree Do?* brochure, a tree is indeed a wonderful "device.")

Sheil concludes that, according to the latest science (not to mention common sense), declining forest cover means less atmospheric moisture flow. And he expresses concern that we've been losing forests, particularly in the tropics.

"The Future Climate of Amazonia" made Antonio Nobre something of a celebrity in Brazil. He had given voice to people's fear: that the drought was not a fluke but an inevitable consequence of the deforestation that had happened under everybody's watch. The report was excerpted and cited countless times, and he gave interviews to journalists around the world. He appeared three times on the Sunday evening news show *Fantástico.* He told me that a national poll found that 40 percent of Brazilians knew about the report and accepted the link between water shortages and the ravaging of the Amazon rainforest.

"For the people in the street, the report made a big difference—that's exactly what I intended," Nobre says. "I'd started to articulate knowledge in a way scientists usually do not do because they are too specialized, packaging it in language that anyone could understand. The beast of knowledge was released. There was no putting it back. I'd see people in the elevator when I was going home, or taxi drivers, and some of them saw me on the Sunday program and they'd say, 'Of course the destruction of the forests is causing the drought.'" Nobre has had the experience of writing scientific books and papers for policy makers, which were "basically ignored. I decided this time I was going to speak directly to the people."

Nobre certainly had a receptive audience, since toward the end of 2014 people were in a constant state of angst about the drought. "I saw fear in peoples' eyes in São Paulo," he recalls. "For the first time, people had become really scared. It was unimaginable: what are we going to do? That fear was something that was deafening—soundless but deafening. There had been droughts in the past, but nothing compared to 2014. In Brazil we have a saying that God is Brazilian: we have good rain and soil and a wonderful climate. And then the joke that the only 'natural disaster' we have is called the National Congress. Now all of a sudden we have floods and we have droughts."

A theory called the "biotic pump," first described in a 2007 paper by Russian physicists Victor Gorshkov and Anastassia Makarieva, adds scientific ballast to the idea that forests are central to the production of rain.[24] Nobre and Sheil have each collaborated on papers with the Russian scientists; the concept is featured in both "The Future Climate of Amazonia" and "How Plants Water the Planet." The Russians' work, presented in the rarified language of atmospheric physics, challenges many long-held ideas about weather and climate. And speaks to the kind of questions a precocious five-year-old might ask, like, "Where do winds come from?" "If the water that falls as rain originated in the ocean, how do places far from the coast get rain?" Or, "Which came first, the forest or the rain that waters the forest?" It's a compelling hypothesis, but one branded with the dubious label "controversial." One biotic pump paper was published in *Atmospheric Chemistry and Physics,* an esteemed scientific journal, only after an unprecedented two-and-a-half-year-long discussion. The article appeared with a special editor's comment stating that its publication did not represent "an endorsement or confirmation of the theory, but rather a call for further development of the arguments presented in the paper for a final conclusion on its veracity (or not)." A declaration like that is unusual, to say the least.[25]

The theory maintains that natural forests act as a "pump" that draws moisture inland. Here's the gist: The concentration of trees in a forest means a high rate of transpiration. When this moist air ascends above the forest it cools, at which point the water vapor condenses. This produces a partial vacuum, a low-pressure zone, where the condensation has taken place. The result is an air pressure gradient, whereby the forest canopy draws in moist air from the ocean. Gorshkov and Makarieva contend that it's this *air pressure differential*—as opposed to a *temperature differential,* as has been assumed—that generates and drives the horizontal winds and flows of moisture that deliver rain.[26]

The biotic pump theory introduces the importance of transpiration to rain patterns. Precipitation isn't just a matter of condensation; it's a manifestation of the ongoing fluxes of transpiration *and* condensation. This principle "explains why in forested regions precipitation does not decrease with distance from the ocean, even thousands of kilometers, while the interiors of deforested parts of continents become dry already a few hundred kilometers away from the oceanic coast," Gorshkov and Makarieva write to me. "Condensation of water vapor over forests creates pressure gradients that have been shown to be sufficient to drive winds that bring moisture from ocean to land."

According to Gorshkov and Makarieva, forests don't merely grow in wet areas; they create and perpetuate the conditions in which they grow. As the physicists write on their website, "The chicken-or-the-egg problem of whether forests grow where it is wet, or it is wet where the forests grow, solves unambiguously in favor of the forests' priority."[27]

They describe a kind of "tug-of-war" between forest and ocean: with its abundance of trees—each busy transpiring moisture—a thriving forest evaporates more water than does the ocean. Thus the wooded area "wins" the tug-of-war and pulls moisture inland where it will fall as rain.

Now things get interesting—and alarming, given situations like Amazonia. Without sufficient forest cover, the Russian scientists say, water vapor is no longer drawn to a continent's interior to the same degree. The forest and the ocean keep on with their tugging, the eternal jousting for atmospheric moisture. But with a different result. Without its transpiration "advantage," the forest no longer pulls in moisture. The pump mechanism has gone bust. Rain becomes erratic and ultimately stalls, much now falling over the ocean rather than on land.

The Russian scientists associate the unusual heat waves and drought in their country over the last several years with the rapid deforestation in western Russia. They've suggested that the burning of coastal forests by Aboriginal settlers in prehistoric times contributed to the drying out of Australia's interior. Could the advent of drought in formerly wet forested areas like Madagascar, Indonesia and parts of Equatorial Africa reflect the waning of the biotic pump in those places?

There's much we don't know, including how the biotic pump interacts with circulation configurations like the Hadley and Walker cells and the El Niño/La Niña oscillations. There's also the question of what kinds of trees support the pump mechanism. Gorshkov and Makarieva say only established native forests have enough biomass to "prime" the moisture pump. They say since forests grow in specific environments—they're part of a living community and therefore develop in relation to other living organisms, down to bacteria and fungi in the soil—only mature, natural forests can fully serve this function. One couldn't substitute a monoculture tree plantation and expect to recreate the conditions of primary forest.

Should the biotic pump be confirmed, it brings new urgency to forest protection. "Most climate models recognize the role of 'precipitation cycling' in forests, but not moisture transport by forests," Makarieva and Gorshkov wrote to me. The difference is significant: if deforestation means simply reduced evaporation, the decline of precipitation would be relatively minor. If, however, rains depend on *imported* moisture and a key vehicle for transport—an intact forest—is impaired, that's a different story altogether. The physicists say, "In our model, imported moisture will decline if the forest is destroyed, especially in the inland portion of the continent. If there is no imported moisture there is nothing to be evaporated, so the water cycle will undergo a dramatic—not minor—reduction of intensity." In the Amazon, they say, this could mean a precipitation decrease up to 90 percent.

Douglas Sheil tells me he encountered Gorshkov and Makarieva's first biotic pump paper around 2007 when he was embarking on a book on conserving rainforest biodiversity. "I was working for CIFOR [the Center for International Forestry Research], collecting information on how we could better protect this forest or that forest," he says. "I was looking at hydrology and found this paper from the Russians. I said to a colleague, 'Do you believe this? If this theory is true, this is really important.'"

Sheil and his CIFOR colleague, Daniel Murdiyarso, decided to look more deeply at the phenomenon and wrote a scientific review, "How Forests Attract Rain: An Examination of a New Hypothesis." Since then he's been in close collaboration with Gorshkov and Makarieva. "I've never said they were right or wrong," he says. What's important is that ideas are made available for discussion: "Let's put it out there. That's how science works."

Something that troubles Sheil greatly is the rapidity with which a region can "flip" from wet to dry. He and Murdiyarso explain: "According to Makarieva and Gorshkov, if the near-continuous forest needed to convey moist air from coasts to continental interiors is severed, the flow of atmospheric moisture stops. Thus, clearing a band of forest near the coast may suffice to dry out a wet continental interior. Further, clearing enough forest within the larger forest zone may switch net moisture transport from ocean-to-land to land-to-ocean, leaving any forests remnants to be desiccated."[28]

Sheil adds, "It's not just local effects we need to think about, but the large-scale circulation systems are probably driven by forests more than we realize." Other researchers, too, have found evidence of teleconnection—climate occurrences in which cause and effect may be thousands of miles apart—associated with changes in forest cover. For instance, climatologist Roni Avissar, now dean of the Rosenstiel School of Marine and Atmospheric Science at the University of Miami, and colleagues at Duke University found that deforestation in the Amazon Basin correlates with lower rainfall not just locally but in distant regions, including the American Midwest.

In his 2014 Ph.D. thesis, R. J. van der Ent of Delft University of Technology used the term *atmospheric watershed* to explain how a rain-dependent region like the Sahel in West Africa may rely on transpired vapor from as far away as southern Europe. Understanding "sources" and "sinks" of moisture can help us assess potential impacts of land cover changes, he writes.[29] It's incredible to think that a farmer in Burkina Faso may enjoy good yields of millet and maize thanks to healthy woodlands in Portugal. However, the use of isotopes and modeling to study moisture recycling is showing us that when it comes to the water cycle, we all live in the same neighborhood.

In Brazil Antonio Nobre has been watching this devolve in real time—or rather, accelerated time. He writes, "Many of the model projections for the consequences of deforestation have already been observed, especially the expansion of the dry season." According to the simulations, however, this wouldn't happen until complete deforestation. At this point, about 18 percent of the Brazilian forest has been clear-cut, fallen to what he calls the "tree guillotine." Another 25 to 30 percent has been degraded, or "wounded." What does this mean in terms of its function? Has the "Future Climate of Amazonia" already arrived?

Research by University of Virginia scientists published in late 2014 in *Nature Climate Change* pointed to dire consequences of deforestation. The authors argue that environmental impacts of forest loss are global and go beyond the release of carbon stored in the trees—a common view of forests' chief relevance to climate.[30] Lead author Deborah Lawrence told the *Washington Post* that the Amazon and central Africa could have a "tipping point" of 30 to 50 percent deforestation, beyond which natural systems could break down.[31]

"We are headed for the abattoir," Nobre tells the Latin American Bureau (LAB), a UK news service.[32]

Nobre's recommendations for avoiding disaster? For one, an absolute halt to deforestation and forest burning. Since that won't be enough, he says, we also need to regenerate natural forests. It's not just about individual trees, he stresses, but the integrity of the forest system. This means restoration on an immense scale.

"The forest is our security, our protection system, like a piggy bank," Nobre tells LAB. He worries about the stress to the Amazon, and says the forest itself is striving to defend against what's been done to it, just like the human body seeks balance upon illness or injury. "The rainforest is working like crazy underneath," he says. "The climate models do not consider the characteristic of life to compensate for stress or abuse. We're led to believe the process of change is slow. But as with an alcoholic, when you've got cirrhosis of the liver it's too late. Earth's systems are responding as best they can. When they start caving, it will be precipitous. We thought [climate effects were] way out in the future because the logic of life is not built in."

He observes that an annual decline in the amount of deforestation in the Brazilian Amazon, which occurred in 2011 and 2012, is met with self-congratulation—as if merely chopping down fewer trees were enough. Laudable as less damage may be, he says, this ignores the ecological implications of the accumulated deforestation that's taken place over time. Given the proportion of the rainforest that has been clearcut or degraded, Nobre fears the Amazon Basin may be approaching a point of no return. Beyond a certain threshold the biotic pump's traction could cease. Amazonia, then, could shift to a new state of equilibrium, more like dryland savanna. In a worst-case scenario, writes Nobre, the humid tropical biome, with all its biodiversity and capacity to sustain the region's agriculture and well-being, "would resemble present-day

Australia: a vast desert interior fringed on one side by strips of wetter areas near the sea."

In other words, the lushest tropical rainforest on the globe could flip from hydration to desiccation, from jungle to desert.

Let's leave the Amazon for a bit and head over to western Kenya, where our friend (and marketer of the ever-popular "tree" air-conditioning unit) Jan Pokorný does fieldwork. Over the last twenty years he's watched the landscape grow drier. He attributes this in large part to deforestation: whereas forests once covered more than half the country, it's now less than 2 percent. Pokorný monitors how vegetation affects the distribution of solar energy, using satellite technology and thermal infrared sensors. It's a plum gig for machine geeks: he takes measurements while flying above the African landscape in a small Cessna. He shared with me an aerial photo of the area between Lake Naivasha and the Mau Forest. The mountain forests measured 19 degrees C; agricultural fields that used to be woodlands hovered close to 50 degrees C. The image shows the dark green of forests diminishing along the slope to the lowlands. The valley has clusters of deep green among the broad, pale, geometric shapes of cultivated land.

Two hundred thousand hectares of forest have been converted to agricultural land over the past two decades, Pokorný tells me. The Mau Forest was long called a "water tower" because it supplied water to the Rift Valley and Lake Victoria. More recently, the region has suffered from drought, especially during 2009's rainless rainy season. The area's gone so dry that a Japanese company stopped construction on a hydro power station; one already built, along the Sondu Miriu River, works only erratically. (The Japanese company behind the project asked the Kenyan government for compensation arguing that they were given poor hydrological data. The problem wasn't the data: it's that the hydrology had changed in the decade-plus since studies were done.) Kenyan authorities have imposed large-scale evictions in the area, ostensibly to stave off environmental disaster. There are frequent protests and skirmishes over logging and burning.

Detreeing the landscape has altered the way the ecosystem functions and self-regulates, says Pokorný. In Kenya, there "used to be a lot of rain forest. Water was constantly evaporating and above the forest the air stayed cool. Now we have agricultural land, often bare, and it's hotter and there's less evaporation. There are more days without clouds and fog. Because the air from the land is hotter, the clouds and fog disappear. The relatively dry air moves over bodies of water that now get more direct solar radiation." He notes that Lake Victoria, a large shallow lake tucked in among Tanzania, Uganda and Kenya, has shown temperature stratification, with warm water on the surface, a situation that threatens its ecological balance.

Pokorný put me in touch with Sarah Higgins, a conservationist who runs the Little Owl Sanctuary (now Naivasha Owl Centre) for injured birds near Lake Naivasha. Higgins says she's seen weather patterns vary with the forest's fortunes. When she started farming thirty years ago "we were almost guaranteed sufficient rainfall for our crops." Then came the destruction of the Mau forest, and the area above and on either side of the farm was "denuded of trees and overgrazed, down to bare earth. Our regular rainfall started to fail and we were seeing dry years, poor yields and more droughts."

However, in the mid-1990s, her late husband, Mike, planted many thousands of trees on areas of the farm that weren't suitable for crops. As these started to mature, says Higgins, "the rain is becoming more regular again. The clouds that have been passing along the Mau looking for somewhere to off-load seem to make a little deviation so that it's over our farm—i.e., our trees! This is a hugely unscientific statement, just a personal observation backed up by our rain records."[33]

Higgins's story is just that: anecdotal evidence based on someone's observations and experience. But there are reforestation projects happening all over the world and lots of similar reports, albeit not scientifically verified. Forested landscapes can be restored; with restoration ecological function does return. Can reforestation bring back the multiple, perhaps immeasurable, ways trees contribute to the water cycle? Is there a point at which there are enough trees to reinstate important mechanisms—a kind of reverse tipping point where things tilt in a positive direction? We don't know. There's no data on the extent to which the biotic pump can be reinstated because these questions have not been asked—yet.

Sheil believes reforestation can revive the biotic pump. "We can fix it. It can fix itself too, if allowed," he says. "Forests do recover . . . impressively." He refers to Ujong Kulong in Java, where you can see monkeys, wild deer and boar under large fig trees in coastal forests—all regrowth after Krakatoa's eruption and subsequent tidal waves in 1883. Since the volcano people have feared resettling the area, and the rainforest has become a national park and UNESCO World Heritage Centre, known for the Java one-horned rhinoceros.

"If we planted trees at a sufficiently large scale it would improve the climate. Even planting on a local scale can improve groundwater recharge," says Sheil. "It is just a matter of will. Think of the amount we spend on the military. If we used half that to fix the planet we'd be getting better very fast."

Nobre urges citizens and decision makers in Amazonia to do everything possible to save and restore the forest as a "healing war-effort." An oxymoron to be sure, but perhaps the language of combat will spark a response; ecological alarm bells like biodiversity loss and failing rains have yet to do the trick. In some circumstances a forest will regenerate on its own, he writes: "There is a wealth of pioneer plant species that have the ability to grow under extreme environmental conditions. These plants establish a dense secondary forest, creating conditions for the complex, lasting tropical forest to recompose itself gradually by medium- and long-term restoration." With large swaths of degenerated land, however, "it becomes necessary to plant native species. If rain still falls, the forest regenerates in replanted areas. A collection of planted trees is better than bare ground, but it is still a long way from rebuilding the functional part of the destroyed ecosystem in all its complexity."

Gorshkov and Makarieva always emphasize the importance of natural forest. The biotic pump, they write, "is a complex information-rich phenomenon," a place-based constellation of biophysical processes that have developed over the course of time. While their research suggests that simply replanting trees wouldn't be sufficient to reinstate the pump, with reforestation "it should be possible to facilitate the natural processes of forest self-recovery." They foresee the advent of "ecological medical science," the environmental equivalent of medical care for people as a means of promoting the healing of disturbed forest ecosystems.

One approach to reforestation is Farmer Managed Natural Regeneration (FMNR), a technique developed by Tony Rinaudo of World Vision Australia that's a rapid, inexpensive alternative to tree planting. Conventional planting is costly, labor intensive and, particularly in harsh, unforgiving environments—such as Niger, where in the 1980s Rinaudo was an aid worker—has high failure rates. While despairing over the blighted landscape, Rinaudo found that even in barren areas, upon closer look you'd find small seedlings and tree stumps that are sprouting. He developed a strategy to give these inchoate trees a chance to grow.

This is done by selection (choosing the most vigorous plants), pruning (steering the plant's energy toward upward growth) and protection (keeping livestock away in the initial months, and ensuring the selected shoots are not taken for firewood). FMNR requires no special skills, Rinaudo maintains. In a film clip he says, "Millions of hectares of land have been cleared in Africa, but the one redeeming factor is that many of the tree stumps are still alive."[34]

As for water, Rinaudo shared in an email some observations from a recent visit to Humbo, in southern Ethiopia. When he first went to Humbo in 1999, the hillsides had no trees. This meant seasonal rains led to floods, "causing deaths, loss of livestock and property, and destruction of crops." He's pleased by the change he's seen. In nearby Soddo the district's water source, which had also been cleared and is now being reforested through FMNR, "thirteen springs have begun flowing again, six of them running all year."

And rain? He continued: "Anecdotally we are hearing that in some areas rainfall does seem to have increased. . . . What is certain is that what rain does fall is more effective—because of lower temperatures, reduced wind speed and lower evaporation and because of increased soil moisture-holding capacity. . . . We are hearing the same testimony from Senegal to Ethiopia and from East Sumba to Myanmar: springs are returning, soils are more moist, water tables are being recharged."

I checked in with filmmaker Mark Dodd, who made *The Man Who Stopped the Desert,* and whose newest film, *Ethiopia Rising: Red Terror to Green Revolution,* looks at restoration efforts in the Tigray region, a mountainous region in the north. "You can virtually see the change in forest cover over ten years from space," he said. "The trees stabilize the hillside. That allows more water to be absorbed. Later on in the year, that helps downstream. We filmed in a wellhead at the end of the dry season. There was still a lot of water pouring out from it."

There's also Dutch scientist Willie Smits's reforestation work through Samboja Lestari, which roughly translates to "Everlasting Forest." He launched the project in 2001, buying up deforested land in Borneo to restore habitat for orangutans, a threatened species he had come to love. He calls them "thinkers of the jungle."

In a 2009 TED Talk, "How to Restore the Rainforest," Smits describes his method, in which sugar palms are planted in rings to block fires. He employs fast-growing trees to provide a canopy for slow-growing rainforest trees. From 2007 to 2009 he reported significant changes. In addition to enhanced biodiversity (the number of bird species rose from 5 to 137), air temperature cooled while humidity, cloud cover and rainfall increased. Reviving the forested area "made it into a rain machine," he said.[35]

The first day of February 2015, the rains returned to São Paulo. "The state government was already planning the rationing of water," says

Nobre. "They were even thinking of leaving people five days without water and then two days with. Companies were beginning to relocate. Then when it started raining, the government canceled everything."

February and March turned out to be a little wetter than average, April less so, he says. "In May, now, it's dry again. Then we have the whole of the dry season ahead. People are scared. It's like a fire that's smoldering—not with open flames, but people know it's there. I think the message about deforestation and drought is there and it has to have time to operate its effect."

Preserving intact forest is imperative. Yet there's also the message about *re*forestation. After all, Brazil already has a model in the Tijuca Forest.

About the Author

JUDITH D. SCHWARTZ is a journalist whose recent work looks at soil as a hub for multiple environmental, economic, and social challenges and solutions. She writes on this theme for numerous publications and speaks at venues around the world. Her 2013 book *Cows Save the Planet* was awarded a Nautilus Book Award Silver Prize for Sustainability and was among Booklist's Top 10 Books on Sustainability in 2014. A graduate of the Columbia Journalism School and Brown University, she lives in Vermont.

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