CLIMATE SCIENCE

Forests Emerge as a Major Overlooked Climate Factor

By GABRIEL POPKIN

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New work at the intersection of atmospheric science and ecology is finding that forests can influence rainfall and climate from across a continent.

Mist hangs over the Amazon rainforest shortly after sunrise. Forests routinely transfer extraordinary amounts of water vapor into the atmosphere — the equivalent of "flying rivers" — and scientists are only beginning to understand the complex consequences for rainfall and climate at remote locations.

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Raphael Alù

hen Abigail Swann started her career in the mid-2000s, she was one of just a handful of scientists exploring a potentially radical notion: that the green plants living on Earth's surface could have a

W major influence on the planet's climate. For decades, most atmospheric scientists had focused their weather and climate models on wind, rain and other physical phenomena.

But with powerful computer models that can simulate how plants move water, carbon dioxide and other chemicals between ground and air, Swann has found that vegetation can control weather patterns across huge distances. The destruction or expansion of forests on one continent might boost rainfall or cause a drought halfway around the world.

Swann is now a professor at the University of Washington, where she runs the Ecoclimate lab. She is in the vanguard of a small but growing group of scientists studying how plants shape Earth's weather and climate. Their results could shake up climate science. "None of the atmospheric scientists are thinking about" how plants could influence rainfall, Swann said, though hints had appeared in the scientific literature for decades. And, she added, "it blows the ecology community's mind … that the plants over here could actually influence the plants over there."

"Many of us are surprised at what a powerful role plants actually play," said Park Williams, a bioclimatologist at Columbia University. "The influence of Earth's surface on large-scale climate is currently a really booming topic, and Abby Swann is one of the emerging leaders in that field."

The Ignored Influence of Plants

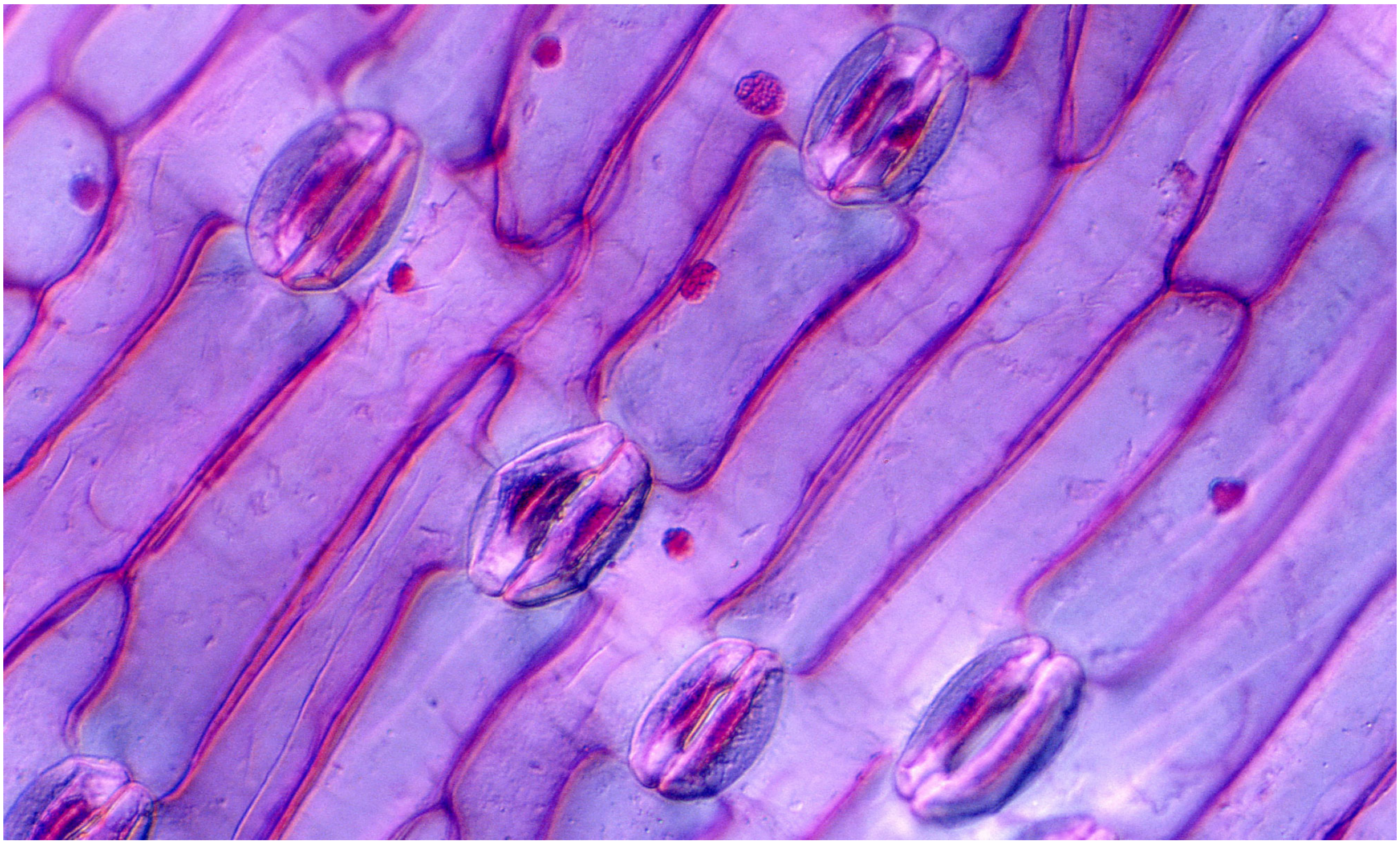
The schism between the atmospheric and life sciences that Swann encountered was a holdover from the late 1800s, when the U.S. government proclaimed that planting crops and trees would turn the arid Great Plains wet. The government had embraced a dubious theory pushed by land speculators and rejected the counsel of one of the nation's top scientists, John Wesley Powell. Spurred on by such optimistic but dubious claims, thousands of would-be farmers headed west, only to find that greening the land did not, in fact, make it rain. Many struggled to scrape a living from the dry ground, and the ill-conceived agricultural experiment eventually contributed to the devastating Dust Bowl.

> "The world's major forests … can move water on almost inconceivably large scales."

Scientists reacted strongly. Early meteorologists, hoping to save their young field's credibility, rejected the notion that forests influence weather. "Much of the discussion of it, unfortunately, has not been of a purely scientific character," one wrote in 1888 in *Science*. Meteorology, and later climate science, became the study of air and water. Plants were relegated to passive participant status.

Atmospheric scientists — and everyone else — could be excused for thinking of a stoically standing tree or a gently undulating wheat field as doing little more than passively accepting sunlight, wind and rain. But plants are actually powerful change agents on the planet's surface. They pump water from the ground through their tissues to the air, and they move carbon in the opposite direction, from air to tissue to ground. All the while, leaves split water, harvest and manipulate solar energy, and stitch together hydrogen, oxygen and carbon to produce sugars and starches — the sources of virtually all food for Earth's life.

The key features of this molecular wizardry are pores, called stomata, in plant leaves. A single leaf can contain more than 1 million of these specialized structures. Stomata are essentially microscopic mouths that simultaneously take in carbon dioxide from the air and let out water. As Swann notes, the gas exchange from each stoma — and indeed from each leaf — is, on its own, tiny. But with billions of stomata acting in concert, a single tree can evaporate hundreds of liters of water per day — enough to fill several bathtubs. The world's major forests, which contain hundreds of billions of trees, can move water on almost inconceivably large scales. Antonio Nobre, a climate scientist at Brazil's National Institute for Space Research, has estimated, for example, that the Amazon rainforest discharges around 20 trillion liters of water per day — roughly 17 percent more than even the mighty Amazon River.



This micrograph of a stained leaf shows the mouth-shaped stomata, or regulated pores, that plants open and close to control the amount of water vapor they release into the air. A single tree can release the equivalent of hundreds of liters of water in a day.

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Josef Reischig

Yet the computer models that scientists rely on to predict the future climate don't even come close to acknowledging the power of plants to move water on that scale, Swann said. "They're tiny, but together they are mighty."

Scientists have known since the late 1970s that the Amazon rainforest — the world's largest, at 5.5 million square kilometers — makes its own storms. More recent research reveals that half or more of the rainfall over continental interiors comes from plants cycling water from soil into the atmosphere, where powerful wind currents can transport it to distant places. Agricultural regions as diverse as the U.S. Midwest, the Nile Valley and India, as well as major cities such as Sao Paulo, get much of their rain from these forest-driven "flying rivers." It's not an exaggeration to say that a large fraction of humanity's diet is owing, at least in part, to forest-driven rainfall.

Such results also imply a profound reversal of what we would usually consider cause and effect. Normally we might assume that "the forests are there because it's wet, rather than that it's wet because there are forests," said Douglas Sheil, an environmental scientist at the Norwegian University of Life Sciences campus outside Oslo. But maybe that's all backward. "Could [wet climates] be caused by the forests?" he asked.

Forests in the Arctic

Swann arrived at the University of California, Berkeley, in 2005 to do her doctoral work with Inez Fung, an atmospheric scientist. In the 1980s, Fung had helped pave the way for climate models that included realistic vegetation and associated carbon dioxide fluxes. (Among her other accomplishments, she was a co-author on the 1988 paper with the NASA scientist James Hansen that helped bring climate change to the public's attention.) The model she worked with was state-of-the-art at the time, but, like its counterparts at other research institutions, it could only represent the biosphere simplistically.

By the mid-2000s, models had improved enough that scientists could more precisely study the role plants might play in the climate system. Fung suggested that Swann try foresting the Arctic in a climate model. Trees are colonizing higher latitudes as the globe warms, so it seemed reasonable to ask what impact they would have on the region's climate. Other researchers had previously looked into the potential effects of an expansion of northern spruce forests; unsurprisingly, they found that the Arctic would likely get warmer because those trees' leaves are dark and would absorb more sunlight than virtually any of the tundra, ice and shrubs they might replace. Swann decided to look into what would happen if the encroaching forests were deciduous trees with lighter colored leaves, such as birch or aspen.

In her model, the Arctic did still warm — by about 1 degree Celsius, which was more than she expected. Swann determined that her simulated forests emitted a lot of water vapor, which, like carbon dioxide, is a greenhouse gas that absorbs infrared radiation from Earth and redirects some of it downward. The vapor then caused ice to melt on land and at sea, exposing darker surfaces that absorbed yet more sunlight and grew even warmer. The new forests had set off a feedback loop, amplifying the impact of climate change. The finding hinted at the power that plants could exert over a region's climate.

Abigail Swann, who heads the Ecoclimate lab at the University of Washington, is at the vanguard of scientists studying how plants can exert an unexpectedly great influence on weather patterns.

Lucas Boland

In a separate study, Swann turned all vegetated areas of temperate North America, Europe and Asia into forest. Again, this exercise exaggerated something already happening in the real world: Satellite data have shown that these continents are greening as former farmland returns to forest, perhaps aided by enhanced atmospheric carbon dioxide and longer growing seasons.

As in the Arctic study, the new trees absorbed sunlight and warmed, adding energy to the climate system. Atmospheric currents then redistributed this energy around the planet. Droughts descended on the southern Amazon and rain fell in the Sahara. These effects were caused by a repositioning of the Hadley cell — the massive conveyor belt of air that rises from the equator, dumps its rain over the tropics, and descends again as dry air at around 30 degrees north and south latitudes, where most of the world's deserts are. Through the influence of plants alone, the Hadley cell had shifted to the north.

Swann had seemingly uncovered a hidden "teleconnection" — a region holding sway over a far distant one through subtle atmospheric mechanisms. Fung wasn't that surprised: Atmospheric scientists have gotten comfortable with such remote influences. In periodic El Niño events, which have been understood since the 1920s, unusually warm surface water in the eastern Pacific Ocean triggers heavy rain in western South America and Africa and droughts in Southeast Asia and Australia. The novelty in Swann's simulated events was that forests, not oceans, did the influencing.

"To me that was a really interesting perspective," said Gordon Bonan, a geoscientist at the National Center for Atmospheric Research in Boulder, Colorado, who also studies the influence of plants on the atmosphere. "If you do enough of this tree planting, you can actually change circulation patterns."

Distant Effects From Forest Changes

Scenarios such as a green Arctic or a reforested temperate zone are not as far-fetched as they may seem. A recent study in *Nature* reported that in the last three and a half decades, tree cover has increased by more than 2 million square kilometers in these regions.

Massive tree losses are also part of our modern world. During roughly the same period when temperate and boreal trees gained ground, some 20 percent of the Amazon rainforest was cut down. Since 2010, nearly 130 million trees have died in California alone, mostly because of drought and wildfire.

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> When she wiped out trees in the Pacific Southwest, forests in the Midwest and eastern U.S. suffered.
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Much effort has gone into understanding how future climate change will affect forests. Based on severe droughts that occurred in 2005, 2010 and 2015, some scientists believe the Amazon may be nearing a tipping point that would cause much of its rainforest to turn to savanna, with potentially devastating consequences for carbon storage, biodiversity and local climate. A paper from late 2017 provided evidence that future warming would make droughts even more lethal to the forests of the American Southwest. Some scientists predict that many of the Southwest's forests could become savanna or grasslands, and at least one — Nate McDowell at Los Alamos National Laboratory — has been quoted as saying that a large fraction of the region's trees could die.

Yet the question of how changes in forests could alter the global climate has barely been considered. “For decades we’ve been looking to see: How well can we do in climate modeling without needing to evoke the influences of vegetation?” Williams said. “Vegetation has kind of been left on the back burner.”

Swann’s and Fung’s research suggested that plants need to be brought to the fore. And other researchers have taken note. Earlier this year, two groups of scientists, both of which included Swann, authored studies of how forest-driven water transport will change as carbon dioxide levels rise. Studies of individual leaves have shown that when plants are bathed in carbon dioxide, they don’t need to make as many stomata per leaf, and they close the ones they do make more of the time. These changes help forest plants conserve water to survive, but they reduce the water vapor available to fall as rain on the surrounding continent. Moreover, when plants transpire, they cool Earth’s surface and warm the air, just as the evaporation of sweat cools your body on a hot day. Leaf-level changes, scaled up across continents, could rob the atmosphere of moisture and warm the planet’s surface.

To Michael Pritchard, a climatologist at the University of California, Irvine, Swann’s results were “very provocative … and a big wake-up call,” he said. “This effect seemed to be rewriting the maps of the drought severity outlook in the future.”

Pritchard said he hadn’t previously been aware of the stomatal closure effect. The knowledge inspired him to join a group led by Gabriel Kooperman, a climate scientist then at UC Irvine, investigating the future effects of enhanced carbon dioxide over the three major tropical forest regions — the Amazon, Central Africa and Southeast Asia.

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> Gordon Bonan, National Center for Atmospheric Research

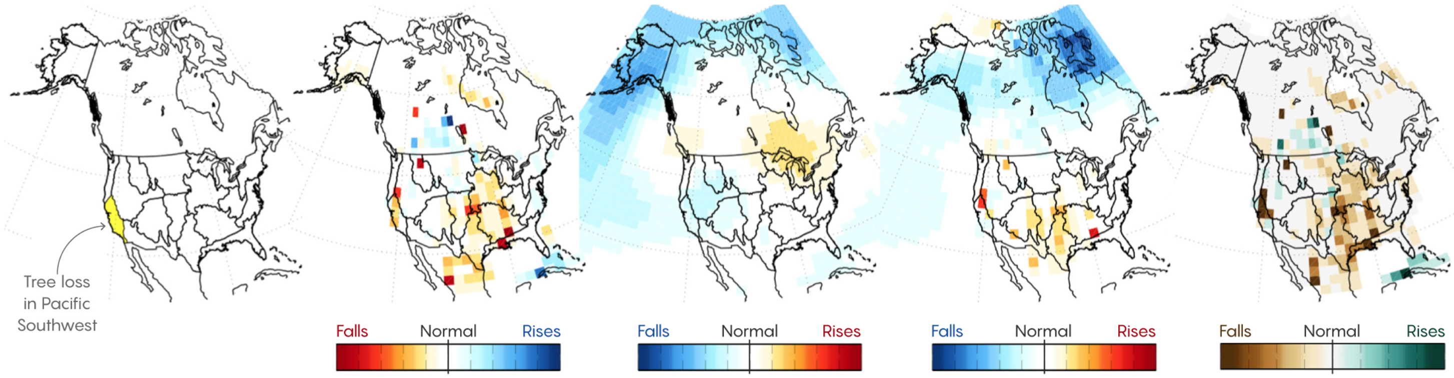
In a study published in *Nature Climate Change* in April, the researchers found that the closing of stomata would cause half the rainfall changes the regions would see by 2100. Moreover, the Amazon — home to the world’s most carbon-rich and biodiverse rainforest — would get hit with the most severe declines.

Swann is now probing the effects of forest changes at different scales. In a 2016 paper, she reported that wiping out forests in western North America made forests in eastern South America grow more vigorously, while reducing growth in Europe.

And in a study published in May, she investigated how U.S. forest die-offs would affect forests elsewhere in the country. In her models, she killed off forests in 13 heavily forested regions that the National Science Foundation has identified as being ecologically distinct. The results were dramatic. When she wiped out trees in the Pacific Southwest, forests in the Midwest and eastern U.S. suffered. In recent years, the Pacific Southwest has, in fact, lost an estimated 100 million trees, mostly to droughts and voracious insects.

Modeling a Forest-Loss Domino Effect

In new computer models, the loss or gain of forests in one place can trigger a chain of atmospheric and ecological changes far away. Wiping out trees on the U.S. western coast, for example, can alter conditions across North America.



Regional forest-loss in the Pacific Southwest has amounted to 100 million trees in recent years and could get worse in the future. →

Transpiration levels (the amount of moisture released from plants into the atmosphere) then deviates from the norm in various regions. →

Atmospheric pressure decreases in most regions but increases slightly in others. →

Surface temperature decreases toward the north pole and increases in parts of the US. →

Gross primary productivity (a measure of plant growth and photosynthesis) decreases over most of the continent.

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Lucy Reading-Ikkanda/Quanta Magazine, adapted from Abigail L. S. Swann et al doi:10.1088/1748-9326/aaba0f

The effects of forest die-off can also be positive, however. In Swann's study, removing trees from the mid-Atlantic actually helped forests elsewhere, by making those regions' summers cooler or wetter. Swann emphasizes that this does not mean people should cut down forests, which provide innumerable benefits beyond their influence on other regions, including carbon storage, wildlife habitat and water filtration. But she notes that environmental groups often plant trees as a climate solution without considering whether the trees could harm forests elsewhere — or warm the planet by absorbing solar energy.

Massive government-sponsored tree plantings have taken place in China and the African Sahel, for example. No one knows what effects they have had on the global climate. "What we would like to be able to say is, if you plant this amount of trees, you would see this reduction in planetary warming," Bonan said. "We don't really quite have that answer yet."

For Swann, it was a thrill to see any effect. "The smaller down in scale we go, I thought it would be harder and harder to identify these climate responses and subsequent forest responses," she said. "These smaller forest losses still do have big impacts, and actually the impact doesn't just scale with the tree area that's lost."

The Uncertainties Still Matter

Not everyone is sold on ecoclimate teleconnections. Sheil is skeptical of the results of the Kooperman-led study. He thinks climate models do not represent plant biology and the physics of air movement and rainfall accurately enough to say anything meaningful about the real biological world. He notes, for example, that different climate models given the same input often make different predictions.

Others point out that ecoclimate researchers have relied largely on one model, the Community Earth System Model, or CESM. Typically, climate scientists aren't convinced that a phenomenon is real until they have seen it in the output of numerous models; for instance, the next Intergovernmental Panel on Climate Change report will incorporate results from more than 30 models. It's possible that the CESM may be unusually sensitive to vegetation, Pritchard said.

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Park Williams, Columbia University

Swann adds a critique of her own: She and her colleagues haven't always been able to piece together the full chain of physical causation through which forests influence distant regions in her models. In her recent paper on U.S. forests, for example, there were too many disparate mechanisms to investigate one by one, she said. The situation is reminiscent of the hypothetical butterfly flapping its wings in Brazil and setting off a tornado in Texas: Swann and her colleagues can set the butterfly fluttering and see the tornado take shape, but they don't fully understand what happens in between. Elucidating such mechanisms will be a focus of future work.

Addressing these concerns won't happen overnight, however. Most models, unlike the CESM, can only be run at a modeling center by the handful of scientists who created them. Those people are busy running simulations for the next Intergovernmental Panel on Climate Change report, due out in 2022. None of the models being used fully account for plants' influence on climate, Swann said.

The historical view that climate science is mainly about physical phenomena still has influence. For more than a decade, climatologists have seen clouds as the biggest source of uncertainty in models. Clouds cool the planet by reflecting incoming sunlight, but they also warm the planet because they are made of water vapor, a greenhouse gas. Models differ wildly on how much clouds will contribute to cooling and warming in the future, and thus whether a doubling of atmospheric carbon dioxide will be problematic but manageable, or catastrophic.

But how much rain will fall in a given region, and when, and how much it will vary season to season and year to year, will make all the difference in determining which places will remain livable and which places won't. And Swann and Fung's results open up at least the possibility that plants could have as much effect as cloud physics on nailing down the answers to such questions.

Moreover, Fung points out, the problems aren't even independent: Forests produce clouds. Without an accurate picture of forests, cloud models will remain incomplete.

That's why Swann is starting a new project: to try to quantify how much plants contribute to the uncertainty in climate model results. With that number in hand, she may have an even more potent tool for convincing other researchers that ecology and atmospheric science are inseparable.

Another potential project involves looking at forest data for observational evidence of the teleconnections found in modeling studies. Swann admits, however, that she's "a little bit on the more skeptical side" that such signals will emerge amid the many pushes and pulls that forests experience. She and David Breshears, an ecologist at the University of Arizona and one of her co-authors on the U.S. forest paper, are also exploring how future southwestern forest losses will affect the climate of the Midwest, the nation's breadbasket and one of the most productive agricultural areas on Earth.

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One thing is clear already: Swann's influence is being felt. In just over a decade, ecoclimate teleconnections have gone from being virtually unknown to appearing as a frequent discussion topic at major scientific meetings such as the Ecological Society of America and the American Geophysical Union. No longer are such ideas dismissed as not being "of a purely scientific character."

The developments in this new research area demonstrate that future climate scientists will need to master two fields that have, for more than a century, been largely separate, Fung said: atmospheric physics and biology.

"There are very few 'multilingual' scientists," Fung said. "When Abby did her thing, it was the coming together of two disciplines." She added, "That's how progress is made."