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The Fate of Trees: How Climate Change May Alter Forests Worldwide

By the end of the century, the woodlands of the Southwest will likely be reduced to weeds and shrubs. And scientists worry that the rest of the planet may see similar effects

By Jeff Tietz March 12, 2015

Scientists warn that, due to climate change, "far greater chronic forest stress and mortality risk" – including from fire – "should be expected in coming decades." Helen H. Richardson/The Denver Post

In May 2011, a postdoctoral student at Los Alamos National Laboratory named Park Williams set out to predict the future of the dominant iconic conifers of the American Southwest — the Douglas fir, the piñon pine and the ponderosa pine. As the planet warms, the Southwest is projected to dry out and heat up unusually fast — few places will be more punishing to trees. Williams couldn't rely on climate models, whose representations of terrestrial vegetation remain crudely unspecific. He needed a formula that could accurately weigh the variables of heat, aridity and precipitation, and translate atmospheric projections into a unified measure of forest health.

For decades, all over the planet, heat-aggravated droughts had been killing trees: mountain acacia in Zimbabwe, Mediterranean pine in Greece, Atlas cedar in Morocco, eucalyptus and corymbia in Australia, fir in Turkey and South Korea. A year earlier, a group of ecologists had published the first global overview of forest health. They described droughts whose severity was unequaled in the "last few centuries" and documented "climate-driven episodes of regional-scale forest die-off." They couldn't prove causality, but if the warming climate was responsible, they warned, "far greater chronic forest stress and mortality risk should be expected in coming decades."

From a tree's perspective, excessive heat may be as deadly as lack of water. To photosynthesize, a tree opens pores in its leaves called stomata and inhales CO_2. Solar-charged chemical reactions then transform the CO_2 into carbohydrates — the raw stuff of leaves and wood. During this process, a fraction of the tree's internal water supply evaporates through its stomata, creating the negative pressure that pulls water from the soil into the tree's roots, through its trunk and up to its canopy. But heat juices the rate at which trees lose moisture, and that rate escalates exponentially with temperature — so small temperature increases can cause a photosynthesizing tree to lose dangerous amounts of water. "Forests notice even a one-degree increase in temperature," says Williams.

In the death scenario, the sky sucks water from the leaves faster than it can be replaced by water in the soil, and the resulting partial vacuum fatally fractures the tree's water column. If a tree closes its stomata to avoid this, shutting down photosynthesis, it risks starvation. Ultimately, the tree's cellular chemistry will fail, but it will often die before that, as its defenses fall; the complexly toxic sap that repels predatory insects dries up. Many insects can detect diminished sap levels within tree bark by scent — they smell drought stress and pheromonally broadcast news of deteriorating tree health. Other defenses – against microbes, for example — may also be compromised. A hotter climate generally means more insects. It also means more, and more intense, wildfires.

Williams amalgamated a millennium's worth of data — the most comprehensive record of forest health ever assembled. Documenting the lives of 10,000 trees, the record spanned the years 1000 to 2007. From it, Williams derived a "forest-drought stress index" (FDSI), the first-ever holistic metric of atmospheric hostility to trees. In a 2013 paper titled "Temperature as a Potent Driver of Regional Forest Drought Stress and Tree Mortality," Williams predicted that by the 2050s, the climate would turn deadly for many of the Southwest's conifers. By then, he wrote, "the mean forest drought stress will exceed that of the most severe droughts in the past 1,000 years."

The current climate was testing his conclusion even as Williams was reaching it. In 2000, the Southwest had entered an extreme, ongoing drought — the worst since a 20-year-long drought in the middle of the last century. Conditioned by near-record temperatures, dry soils and a lack of rain, the atmosphere stripped trees of moisture with exceptional force. "That extreme evaporative demand was a hint of what you'd see if you increased temperatures by a couple of degrees, as the models predict for the 2050s," Williams told me. In terms of precipitation levels, the mid-century drought was worse, but humans had spent the intervening 50 years heating up the planet, and the drought of the 2000s has consequently killed many more trees.

"It was like looking through a telescope into the future to see how forests would respond, and it felt awful," Williams says. "The result was totally unimaginable: wildfires, bark beetles, a huge reduction in forest growth, massive mortality. In the afternoons, I'd go on jogs on the trails outside my office and take mental inventory of who was dying and who was living. All over New Mexico, trees keeled over. It was like they'd been transported onto a new planet where climate is entirely different than what they were evolved for."

Dead Ponderosa and Pinon pine trees stand out among the few green trees that are still alive near Los Alamos, New Mexico. The trees have been stressed by years of drought. Phillippe Diederich /Getty

At the hottest, lowest edge of the local ponderosa pine range, where trees already lived at the limit of what they could tolerate, the future seemed to have arrived. "Watching those trees die, I was aware I was also watching that species' geographic distribution change," Williams told me. "It looked slow to me, but on the time scales that these trees work on, the transition was a flash, like a border being suddenly constructed, and the few unlucky ones on the wrong side being sentenced to death."

Williams' postdoctoral adviser at Los Alamos, Dr. Nate McDowell, an expert on mechanisms of tree death, had been concurrently conducting his own experiments on conifers in the wild. He'd erected a series of clear Plexiglas cylinders around individual piñon pines, and systematically heated and dried them while monitoring their vital signs. Simulating climate conditions for the remainder of the century, McDowell could see in his

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Plutonian chambers what Williams had foreseen. "The Southwest is going to be a grassland, with the occasional rare tree," McDowell says. "It's going to be a different place. And there's reason to think that's the same for big chunks of the world."

All trees share an essential anatomy and physiology; they employ corresponding mechanisms to fight insects, to transport water, to make food, to outlast drought. They have the same vulnerabilities. Because global warming outpaces evolutionary adaptation, the question is: Can they survive as they are? The conifer forests of the Southwest, if climate projections are even minimally accurate, cannot, but what about the rest of the world's forests?

That's a critical question, because forests cover more than a quarter of the planet's land, and they help stabilize the climate by pulling immense quantities of CO_2 out of the air. Of the 36 billion metric tons of CO_2 humans emit annually, about 50 percent rises into the atmosphere and about 25 percent falls into the oceans, but around the time that Williams began deriving the FDSI and McDowell was clinically enfeebling trees, no one knew exactly how much of the remaining 25 percent forests drank in.

The answer turned out to be virtually all of it. In August 2011, a team of scientists led by Dr. Yude Pan, a U.S. Forest Service researcher, reported that between 1990 and 2007, forests sequestered about 25 percent of all greenhouse-gas emissions — everything not in the air or seas. "Forests… exert strong control on the evolution of atmospheric CO_2," Pan wrote. They constituted a gargantuan "terrestrial carbon sink."

But forests don't just store carbon, they also emit it; a decomposing tree is a smokestack. Climatologists worry that if forests across the planet deteriorate, they could, on balance, begin releasing as much carbon as they absorb. "Climate models don't currently represent terrestrial processes very well," one of Pan's collaborators, Dr. Richard Birdsey, told me. "But if the carbon sink in forests fails, a simple speculation is that global temperatures would increase proportionally to the increase of CO_2 concentration, so about 25 percent above current climate projections."

"The more forests die, the less carbon they take out of the air, the warmer it gets, the more forests die," McDowell says. "It's a thermostat gone bad."

Williams has analyzed climate and tree-health data from the dry forests of inner Asia, including northern China, Mongolia and Russia. "I saw the same thing that I saw in the U.S. Southwest," he told me. "Just a small temperature increase was too much for trees in the driest places to handle." McDowell predicts "massive mortality." By 2100, he believes, rising temperatures could kill more than 50 percent of the conifer forests in the Northern Hemisphere. "I expect global-scale conifer loss," he says, with "major mortality throughout the temperate and southern boreal regions." This would result in a "massive transfer of carbon to a decomposable pool."

By 2020, the worst mountain-pine-beetle outbreak in Canadian history will have added an estimated 270 million metric tons of carbon to the pool. Abetted by uncommonly warm temperatures, the beetles have killed hundreds of millions of trees across swaths of British Columbia cumulatively the size of Missouri. Between 2002 and 2007, and again between 2010 and 2012, the Canadian government reported that insect and wildfire activity had converted its enormous managed forests into carbon sources.

Scientists Williams, McDowell and Allen (from left) think the Southwest's recent drought is a grim preview of the future. Michael Clark

You could add to the endangered list every forest on Earth whose local climate does not get wetter than it is now — without the protection of additional water, heat will eventually turn the air around the forests hostile. Crucially, though, the planet as a whole will get wetter. Global precipitation is estimated to increase roughly 2 percent for every degree Celsius of warming. That will happen largely where it's already wet, and precipitation has begun to intensify in rainy places: Some forests in the eastern U.S. and eastern Canada, for example, are thriving. Most tropical forests will receive more rain, and they account for 70 percent of all the carbon sequestration by forests worldwide. And there will be simultaneous benefits: Warmth lengthens temperate forests' growing season, and extra CO_2 in the atmosphere acts as tree fertilizer.

But wet forests are not expected to be exempt from drought, and those droughts will likely be more frequent and deadlier. The forests of Quebec and Suriname might grow spectacularly for 50 years or more, absorbing ever more atmospheric carbon, and then endure spectacular injury. "All of a sudden, finally, the 100-year drought hits, but it's 4 degrees Celsius warmer than it was before, and kaboom!" McDowell says. "Random wildfires, huge insect outbreaks, mass death." Mortality will blow through the forests, and the wood-locked carbon will be released in unthinkable quantities.

In 2005 and again in 2010, when a historically intense drought struck the Amazon rainforest after a century of rising temperatures, trees burned and died in huge numbers, and their corpses began expelling 10-year or 50-year or 100-year stashes- of carbon. Moist, CO_2-fertilized forests may be able to continually recover from severe droughts — regrowth will be climatically supercharged — but staccato, carbon-exuding die-offs, in combination with emissions by all the degraded and dying trees in drier regions, might tip the global forest sink toward carbon neutrality or net-positive carbon emission. "The more forests die, the less carbon they take out of the air, the warmer it gets, and the more forests die," McDowell says. "It's a thermostat gone bad."

But, says Dr. Stephen Pacala, a leading climate modeler and a professor of biology at Princeton, no one knows for sure. "If the carbon sink in forests fails, we will see big losses in the weight of the biosphere," he says. "If the sink increases, we'll see big gains. This is a big deal, a qualitative difference — and the stakes are terrifyingly high."

The better we understand climate change, the more we seem to find that warming begets warming in unexpected and self-amplifying ways: Implacable heat engines materialize and run independently of all human effort. There are an estimated 1 trillion metric tons of frozen carbon in the soils of the Arctic region — a century's worth of global emissions, twice the amount stored in the global forest, another few Industrial Revolutions. As the planet warms, permafrost thaws and decomposes, sending carbon into the air and further warming the planet. Higher temperatures also kindle increasingly intense and frequent wildfires in high-latitude forests, to quadruple effect. Fire releases carbon directly; it burns off the insulating upper layer of vegetation, exposing more permafrost to warm air; it blackens the trees and land, which consequently absorb more solar radiation; and its soot can settle on and darken snow and ice sheets to the north, which then also absorb more solar radiation. Each effect speeds warming, in turn multiplying wildfires. Other major feedbacks, still insufficiently modeled, are in operation around the globe. Pacala calls these kinds of feedbacks "monsters behind the door." "It's just a question of when they come out," he says.

In theory, if global warming accelerated uncontrollably and the most extreme temperature projections proved preposterously low, average evaporative demand could suction water from the world's trees with such magnitude that their hydraulics would implode. Precipitation would be irrelevant because the uptake rate through any root system is finite – trees wouldn't be able to replenish their water supply fast enough to offset negative pressure, and their pipes would break.

"The pessimist's case is that every tree is tuned to deal with only a very specific range of drought stress and evaporative demand," Williams told me. "And as warming continues, trees constantly see new records being set in terms of evaporative demand, and eventually they're all carried outside of their range of survivability."

But neither Williams nor any other scientist I spoke with thinks the Earth will lose all of its forests. There may be hope in trees' diverse genetic capabilities. They can reduce water and carbohydrate demand by strategically self-amputating, for example, or by radically shifting resources to root systems so that growth occurs profusely below ground while canopies retract.

There are other potentially mitigating factors: Trees become more water-efficient in CO_2-rich air (they're pulling in so much carbon per second that they can limit water loss); forests exert some control over local hydrological cycles (exhaled water vapor increases humidity) and could perhaps carve their own moderate microclimates out of the extreme atmosphere; and species with ultralight seeds designed for wind dispersal might find a way to slowly migrate north as temperatures crest.

Boreal forest in Quebec, Canada. DeAgostini/Getty

And plenty of forests will survive in climatic pockets ecologists call "refugia." Imagine a mountainside above the cold Pacific, or a high-altitude, perpetually shaded valley with year-round stream flow, into which cool night air pours and then pools.

Undeniably, though, tree casualties in the 21st century will be high. Many forests in the drier parts of the world will surrender and disappear — as is observably happening — and will be replaced by scrubbier, more promiscuous organisms: fast-growing grasses and shrubs that can better tolerate heat, drought and fire. A prominent research ecologist at the U.S. Geological Survey, Dr. Craig D. Allen, refers to a future dominated by such ecotypes as "weed world." The ecological reorganizations, Williams has written, will be "unfamiliar to modern civilization." In the U.S. Southwest, droughts, wildfires and insect infestations have already created broad landscapes of dying trees destined to become brushland. By the second half of the 21st century, decades of percussive heat waves will have segued into a permanent heat drought, and brushy flora will have largely supplanted conifer forests. The desert floor will have climbed the slopes of the mountains. El Paso will move to Albuquerque, and Albuquerque will move to Colorado Springs.

That remade landscape might seem ugly to the old eyes of the millennials — a degenerate ecosystem, an affront to ponderosa groves transpiring in memories. But Southwesterners born in 2045, young during the time of greatest disturbance, of spontaneous flame and beetle hordes and in-burst wooden veins, might find the Southwest of 2075 — arid-clean, horizon-inclusive, containably fiery — far preferable to the charnel forests of their earliest recollections.