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Sequoias and Redwoods in a Hotter World: When Trees as High as 30-Story Buildings "Die on Their Feet," Something's Wrong

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The General Sherman tree emerged like something fearfully beautiful—something out of a dream. I had just parked in a lot at Sequoia & Kings Canyon National Parks, on the western slopes of California's Sierra Nevada. I followed a winding concrete walkway that led into a thick and quiet grove of sequoias. A multitude of tourists gathered around one tree—the thickest, widest tree I had ever seen. The General Sherman tree, named after Civil War General William Tecumseh Sherman, towered 275 feet above me, measured nearly 103 feet in circumference, and weighed 1,385 tons. The trunk faced me like a behemoth, and the base of the tree resembled enormous elephants' feet planted against the earth. I felt small.

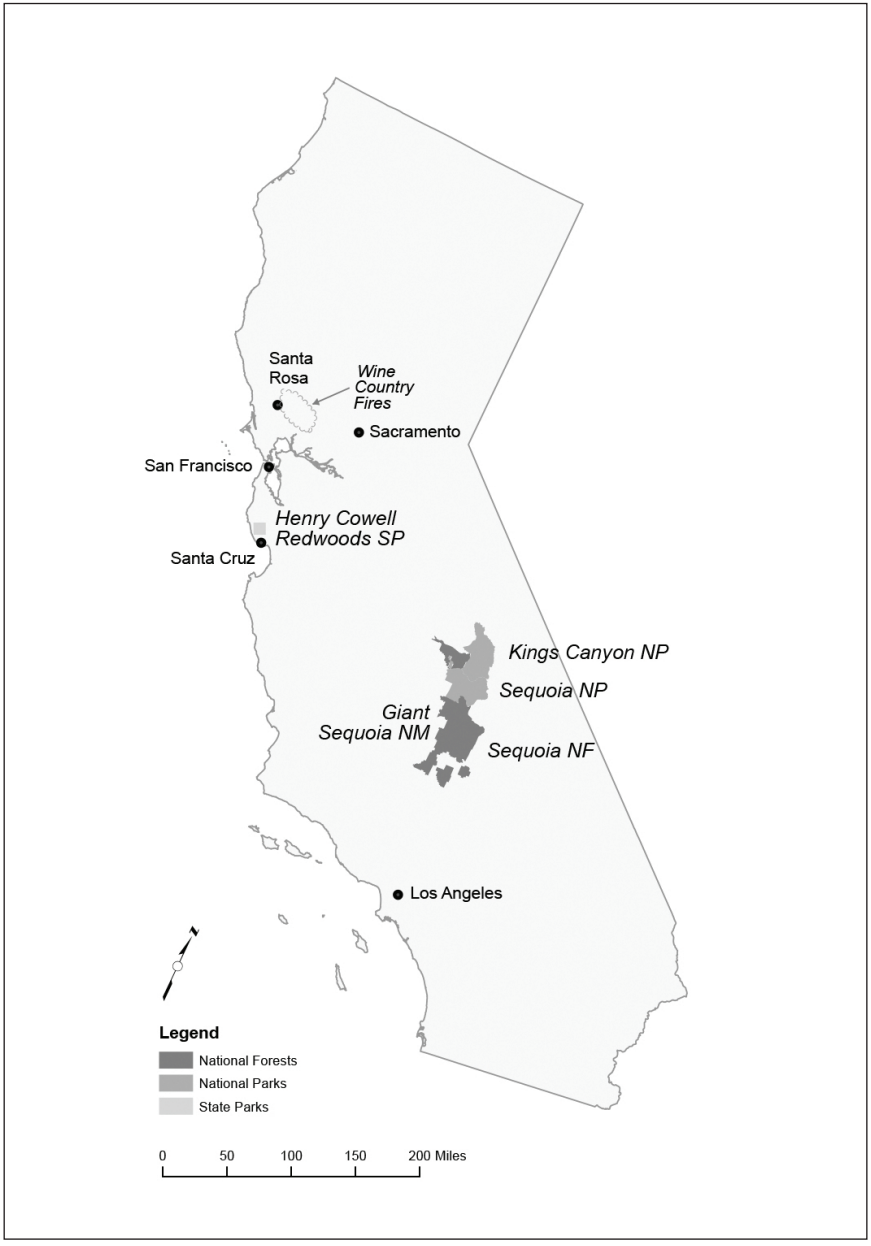
A few days later, I visited Henry Cowell Redwoods State Park, less than five miles north of the coastal town of Santa Cruz, California. The park's famous 40 acres of old-growth coast redwoods stand packed more tightly together than the sequoias. Redwoods' trunks are slimmer, deep ridges gully their bark, and the crowns soar some 300 feet high into the beckoning sky.

I called my trip the big-tree tour. I would inquire how the magnificent giant sequoias and redwood forests have survived California's devastating 2012–2016 drought and explore whether these forests will survive as the earth grows hotter and drier over the next century. Most climate scientists expect global temperatures to increase by at least 2 to 4 degrees Celsius by the end of the 21st century.

What started me on this journey was my stark realization over the past year that the world's forests—which absorb 8.7 billion tons of greenhouse gases per year, or almost one-third of what humans emit—are in crisis mode due to climate change. In 2010, Craig Allen, a research ecologist for the U.S. Geological Survey, and several colleagues documented 88 forests around the world that have been devastated by drought and heat stress. On nearly 25 million acres of forestland in western North America, numerous species of trees have died since 1997. Drought, disease, and insects have killed millions of trees in southern Europe. In Central and South America, widespread drought has exacerbated the catastrophic destruction of rainforests caused by logging and unregulated development.

Are the horrifying effects of climate change threatening California's ancient sequoias and redwoods—arguably the most iconic trees in the world?

University of California, Berkeley, scientist Wendy Baxter climbs a redwood. Back in the lab, researchers study small branches for the drought's effect on the trees. ANTHONY AMBROSE



Redwoods have thrived over a wide area of coastal California, from west of Sequoia National Forest to about fourteen miles north of the California–Oregon border. The author visited Henry Cowell Redwoods State Park near Santa Cruz. The giant trees escaped damage from the 2017 wildfires in wine country near Santa Rosa. LARRY GARLAND/ APPALACHIAN MOUNTAIN CLUB

These are trees with enormous aesthetic, recreational, and spiritual value. The oldest of them date back more than 3,000 years, linking our present to the ancient past. Giant sequoias (*Sequoiadendron gigantea*) grow in 75 groves on the western slope of the Sierra Nevada at altitudes between 5,000 and 7,000 feet, where the snowpack typically builds up to about 45 inches and can last into early summer. Although the sequoias are not as tall as redwoods, they still tower above the earth, and their trunks bulge wider and thicker than those of the redwoods.

The amazingly diverse ecosystems in Sequoia & Kings Canyon National Parks nurture more than 2,000 species of plants, plus 194 species of birds, 85 mammals, 13 amphibians, 25 reptiles, and 9 fish. The parks' most important waterways, Kings River and Kern River, feed water to the rich farmlands of the southern San Joaquin Valley.

Coast redwoods (*Sequoia sempervirens*) grow in a narrow belt along the West Coast, extending from the southern border of Monterey County to about fourteen miles north of the California–Oregon border. They're the tallest trees on Earth, topping out at about 360 feet. They require ample moisture, and during California's dry summers and autumns, they depend on fog along the coast. The "fog drip" can provide between 25 and 50 percent of the water that the trees absorb.

Redwood forests support more than 200 plant species, ranging from the large—Douglas firs and western hemlocks—to small plants like the tiger lily, the Pacific starflower, and the Pacific bleeding heart. These forests also provide habitat for more than 200 vertebrate species and numerous invertebrates. One of them, the bright yellow banana slug, crawls along the forest floor at Henry Cowell State Park. The University of California at Santa Cruz made Sammy the Slug the school mascot!

Scientists in two pioneering research projects are examining how a hotter and drier climate affects redwoods and sequoias now and in the future. The researchers work for the Redwoods and Climate Change Initiative (RCCI), which combines five organizations: Save the Redwoods League, which has been protecting redwoods since 1918; Humboldt State University; the University of California, Berkeley; NatureServe (a group established in 1994 originally called the Association for Biodiversity Information); and the Sempervirens Fund, which was founded in 1900 to protect coast redwoods.

The RCCI scientists established a baseline of forest conditions between 2009 and 2012, when they studied several plots of old-growth redwood

forests. Since then, they have returned to the same plots every year to gather data about the survival rate of trees, changes in local weather, fluctuations in the production of wood, rates of carbon storage, and evidence of biodiversity in the forests.

The U.S. Geological Survey has initiated another effort, the Leaf to Landscape Project, in collaboration with the Integrative Biology Department at UC Berkeley, the Carnegie Institute for Science at Stanford University, and the National Park Service staff at Sequoia & Kings Canyon National Parks. Through this initiative, botanists map areas of the sequoias and redwood forests that show signs of stress, particularly from California's most recent drought.

The RCCI researchers study the sequoias and redwoods in three ways. First, researchers climb the trees. The pioneer in this remarkable enterprise is Dr. Steven Sillett, the Kenneth L. Fisher Chair in Redwood Forest Ecology at Humboldt State University and the subject of the 2007 bestseller *The Wild Trees* (Simon & Schuster), by Richard Preston. Climbing trees is very different from climbing rocks. Tree climbers use a system of ropes and a harness to pull themselves up into the canopy of a tree, moving as lightly as possible on limbs. They wear soft-soled shoes to avoid damaging the tree as they ascend. Sillett and other researchers observe, take notes, collect samples, make measurements, and take photographs. They have discovered that redwood canopies teem with complex communities of lichen, mosses, mites, and other flora and fauna. Yet Sillett fears that redwoods may be an endangered species. "They [redwood forests] were reduced to scraps by us," he told Preston. The length and breadth of redwood forests has shrunk dramatically, making them more vulnerable to the potential ravages of a warming climate.

UC Berkeley scientists also climb trees. Dr. Anthony Ambrose, a post-doctoral researcher in the Department of Integrative Biology, leads the team, which includes Wendy Baxter, a staff research associate. "Berkeley was advertising for someone who was interested in climbing tall trees," she says, "and that appealed to me." Baxter is a scientist, yet she speaks with the touch of the poet when she describes what it's like way up there. "With the giant sequoias, the forests are very open, and the limbs are similar in a way," she says. "They're these massive big limbs going in bizarre directions. Sometimes you feel like you're in multiple trees.

"With the coast redwoods," she continues, "it's quite a bit more dense. It's just very beautiful and complex. It's the same with the structural complexity

Wendy Baxter at work. The researchers do not reveal the whereabouts of the trees they study. ANTHONY AMBROSE

of the older trees. They get all these reiterated trunks and interesting weird burls coming out of them. In some ways, the coast redwoods are a bit more interesting up in their canopies just because of how much can grow in them."

The researchers snip small branch cuttings, bring them down to the ground, and place them into a pressure chamber to measure the amount of stress from drought. Researchers then carry branches back to the lab to measure more closely the water content and other chemicals indicating the level of stress a tree is experiencing.

The second mode of research is gathering and monitoring data. Leaf to Landscape Project researchers study large tree populations over long periods of time—30 separate plots, some for as long as 34 years. The data provide a baseline for understanding the changing conditions in the forest ecosystems.

Third, USGS uses remote sensing and mapping to monitor the changing conditions of forests. From airplanes, researchers use remote-sensing technology to create three-dimensional maps of the crowns of trees and to collect data about the water content of the crowns. In those maps, colors indicate

the water content. Warmer colors, such as red, signify lower water content. By using this technology, researchers can measure more precisely the water content of sequoias and identify which stands of trees may be vulnerable in a hotter, drier future.

Researchers are calling California's recent five-year span of dry weather a "hotter drought"—one that's longer, more intense, with higher temperatures than was typical of droughts in the past. Dr. Nate Stephenson, a research ecologist since 1979 for the USGS at Sequoia & Kings Canyon, has embraced the term, which researchers first coined in 2015. Stephenson's hair and beard are graying, but he looks as if he could walk twenty miles through wilderness without breaking a sweat. He speaks carefully and precisely, reflecting his scientific training. "If, indeed, these warmer temperatures are human-induced, the severity of this drought was pushed into new terrain by warmer temperatures," he says. "You can say that was a signal of climatic change."

So, how did the redwoods and the sequoias fare during California's recent hotter drought? Baxter answers, "What we found with our work is that the giant sequoias weathered the drought pretty well in comparison to a lot of the species. We think that some of that has to do with how insect-resistant they are and how big and old they are. They've developed pretty extensive root networks that can help them during dry times."

The finding is consistent with data showing that redwoods and sequoias have actually increased their growth rates in recent decades as mean temperatures have edged upward. According to Emily Burns, the science director for Save the Redwoods League, "The pattern that has emerged in the last century is that most redwood trees are growing faster than we would have expected, especially in the later decades of the twentieth century. The wood production rates have been higher."

Yet as the researchers have delved deeper into the health of the forests, their findings paint a more troubling picture. Emerging data indicate that sequoias and redwoods could face serious challenges—and even dangers—over the next 50 to 100 years. Stephenson, for example, expected that if any trees showed signs of stress during the drought, they would be seedlings. "I was wrong," he confesses. "I crawled on the forest floor looking for effects of the drought, and the seedlings all looked happy. But the mature sequoias—some of them—were starting to shred foliage in a smart response to drought.

They wanted to reduce their leaf area to reduce water loss. A lot of sequoias were shedding their older leaves."

Burns interprets the foliage dieback as a sign of danger for the future. "If our water resources start to decline," she explains, "all of a sudden these trees will experience much longer periods of water deficits. That's when we have to figure out when they will reach a threshold when they don't have enough water. We're not seeing that now. But when I think about long-term, that's the number one concern."

Coast redwoods absorb water from the fog that rolls in along the California coast. "The fog is really important for them," Baxter says. "It provides an additional water subsidy. It also cools the temperatures down to create a less stressful environment for them." A study published by UC Berkeley in 2010 found that fog along the coast has declined significantly over the past 100 years. The loss in summer fog has ranged between 56 percent and 42 percent, meaning a loss of about three hours of fog a day. According to Todd E. Dawson, the co-author of the study, "If the fog is gone, we might not have the redwood forests we do now."

Researchers are also alarmed that insects could infest the big trees in the near future. Insect infestations have already wrought havoc with other tree species. Since the early 1990s, bark beetles have destroyed millions of trees in the western United States, and the U.S. Forest Service has concluded that warmer summers and shorter winters have created conditions more susceptible to beetle outbreaks. Beetle infestations have slowly moved north from the American Southwest into the Sierra Nevada. Stephenson explains that since the beginning of the California drought in 2012, Sequoia & Kings Canyon have lost 60 percent of their large pines. "The severity of the drought stressed enough trees that these beetles could build up huge populations," he says.

Stephenson warns that even though sequoias have so far resisted insect infestations, warmer temperatures could make the trees more vulnerable. Giant sequoias, which can survive for upward of 3,000 years, typically die when the weight of a tree causes it to become unstable and topple over. Stephenson explains, "In my entire career up until 2014, I'd seen only two giant sequoias die on their feet. During this drought, I'm aware of fourteen others in the park that died standing on their feet. Another four died on their feet in the nearby national forest." The culprit might be the native cedar bark beetle. "It looks to us as though this beetle has riddled the trees that died

Looking straight up into the redwoods: The centerpiece of Henry Cowell Redwoods State Park, near Santa Cruz, California, is its 40-acre grove of old-growth coast redwoods. The trees reach heights of about 300 feet and are between 1,400 and 1,800 years old.
CHRISTOPHER JOHNSON

standing," Stephenson says. The deaths of those fourteen sequoias point to the potential consequences of a warmer future.

Perhaps the most ominous new threat is the growing frequency and intensity of wildfires—a threat burned into the public consciousness by the horrendous fires that tore through California in 2017. Joe Fontaine, a retired high school physics teacher, Sierra Club activist, and longtime champion for the big trees, took me out onto the 300,000-acre Giant Sequoia National Monument—a protected segment of the larger Sequoia National Forest. Pointing to the bark of a sequoia, which can be as much as two feet thick, he explains, "It insulates the tree. When fire comes through, it doesn't burn the cambium."

Sequoias depend on low-intensity fire to open their cones and drop their seeds, expose soil so that seedlings can grow, and open up the canopy to allow sunlight to reach the forest floor. However, for nearly a century, forest

managers suppressed fires, and according to Stephenson, "Sequoias pretty much went through a century of no reproduction during fire exclusion." Since the 1960s, forest managers have used low-intensity prescribed burns to encourage successful sequoia reproduction.

Yet wildfires are growing more intense, partly because of drier conditions and the buildup of undergrowth. As a result of these conditions, wildfires decimated thousands of acres of forestland in northern California and southern California during the dry summer and autumn of 2017. Five wildfires spread across Yosemite National Park, choking the park with smoke. One of those fires raced south to Nelder Grove, a stand of 100 giant sequoias, and scorched the trunks of numerous trees. Scientists are concerned that as the climate grows hotter and drier, wildfires will grow hotter, more intense, more destructive. "One of the things I worry about," Baxter says, "is a big fire coming through and because there's such a large fuel load, it could actually kill some of those big old trees."

Aside from drought, insects, and wildfires, scientists worry about forest fragmentation—the division of forests into smaller segments through road building, logging, and conversion to other uses. According to Burns, "Fragmentation is bad. We've studied what happens to trees on the edge of a forest, and everything from the weather conditions to the types of rain are very different on the edge of a forest versus the interior." The larger the forests are, the healthier they are.

Yet fragmentation is a very real threat because of logging and conversion of forestlands to other uses. The sequoias in the national park are protected, but those in the national monument are at risk. In early 2017, the Trump administration ordered a review of the status of 27 national monuments, including Giant Sequoia National Monument. The review could mean reducing the amount of protected forest—and opening the sequoia forests to logging. Fontaine warns, "If you log, then you reduce the canopy. More sunlight hits the forest floor and melts the snowpack." Interior Secretary Ryan Zinke excluded this monument from boundary or rules changes in September 2017, but the status could still change.

The coast redwoods, meanwhile, face growing pressures from residential development, commercial development, and conversion to vineyards. According to Save the Redwoods League, approximately 25 percent of the original redwood forests—about 625,000 acres—have been converted to other uses. "Redwoods have a role in fighting climate change," Burns emphasizes.

"They grow so quickly. They sequester carbon in this amazing wood that doesn't decay easily. So we need these forests to thrive and to bring back the forests that have been harvested."

The multiple threats of climate change have prompted extensive planning by the National Park Service and other federal agencies. According to Stephenson, the NPS is entering a third era of natural resources management. The first era, which coincided with the founding of the National Park Service in 1916, emphasized tourism and spectacular vistas such as the Grand Canyon. The second era, heralded by the publication in 1963 of *Wildlife Management in the National Parks* (National Park Service)—also known as the Leopold report after its lead author, Starker Leopold (the naturalist writer Aldo Leopold's son)—emphasized entire ecosystems and the protection of natural processes. The Leopold report stated that a national park should preserve "a vignette of primitive America."

In 2012, another seminal report, *Revisiting Leopold* (National Park Service), asserted that national parks are entering a third era. Stephenson writes that in this rapidly onrushing era, "Rapid, unprecedented global changes—particularly climatic changes—preclude key aspects of the Leopold vision, most notably the maintenance of natural resources in conditions that resemble those of the past." *Revisiting Leopold* posits that agencies should manage forests and other natural areas for "ecological integrity" rather than the preservation of the past. Species are going to move, some species will decline in population, and others will become more populous. Yet as much as possible, forest managers should maintain "regional native biodiversity."

The NPS staff at Sequoia & Kings Canyon National Parks has played out four different scenarios and their impact on the sequoia ecosystems. "What would a warmer, drier future look like?" Stephenson asks. "What would a warmer, wetter future look like? What would a much warmer, much drier future look like? They created some scenarios and gamed out an array of possible futures. How can we manage today to maximize our options given the uncertainties?"

Forest managers plan several strategies to strengthen the ecological health of these forests. They will burn sections. In addition to encouraging tree reproduction, prescribed burns reduce fire hazards—the fallen branches and the undergrowth that feed wildfires and make them burn hotter. The NPS has a regular program of prescribed fires at Sequoia & Kings Canyon National Parks, but Sequoia National Monument, which is managed by the

U.S. Forest Service, is another matter. "The problem is not that the Forest Service doesn't want to do it," Fontaine says. "They're not given the money to do it. Logging does not reduce the fire hazard. In fact, it makes it worse. Since 1970, I've advocated for prescribed burning as the way to reduce fuel." For years, though, the Forest Service has had to shift money from other parts of its budget, such as prescribed burns, to pay for fighting wildfires.

Forest advocates believe that protecting more land will prevent forest fragmentation, and help plant and animal life survive as mean temperature rises. Burns says, "For wildlife, there are many species that only live in the center of a redwood forest. If we can grow our forests to be larger, we're going to expand habitat for many species." Consequently, the league is buying land where old-growth forests grow. Burns adds, "We're buying the connecting forests, which may have already been harvested and are within giant sequoia and redwood watersheds. We recognize the connection between where you find old trees and the surrounding habitat, which may have become very altered in the last 100 years but still are really critical to the future."

Forest advocates are mobilizing a new strategy: assisted migration, or human intervention to establish species outside their traditional geographic ranges, giving them a better chance of adapting and surviving a warmer climate. On December 10, 2016, for example, the Archangel Tree Archive Project initiated a program to plant 300 coast redwoods in Seattle and other cities around Puget Sound. The organization propagates saplings from cuttings taken from the stumps of old-growth redwoods—so-called "mother trees."

What can citizens do to help the sequoias, the coast redwoods, and the forests in our own backyards survive the changing global environment? Volunteer for training as a citizen-scientist to help gather data about forests. Advocate for adequate budgets for the National Park Service and the U.S. Forest Service to provide the stewardship that our precious forest resources deserve. Support the continued acquisition of protected forestlands to combat habitat fragmentation. Learn more about assisted migration of species.

Climate change poses multiple threats to these wondrous trees—the oldest living beings on Earth. When I last wrote about climate change in a national park, I focused on Glacier National Park ("High-Altitude Melting," *Appalachia*, Winter/Spring 2017). There, the climate-related changes were stark and unavoidable: the shrinkage of glaciers. In the sequoia and coast redwood

forests, the changes are subtler. Yet Baxter paints a blunt picture. "We're looking at more than two degrees Celsius increase in temperature," she says. "All bets are off once we start getting into the 2- to 4-degree increases. I don't think we can expect that the plants and animals that live there now will live into the future."

Baxter gives voice to an essential truth. Local actions have global consequences. Climate scientists have described for years what people need to do to slow climate change: transition to renewable energy sources. Make buildings and transportation sources far more efficient, as both sectors remain major emitters of carbon. Reverse deforestation and restore forestlands and grasslands, not only because they sequester carbon but also because they provide native habitat for diverse species. These forests speak to us as we wind our way through them and drink in their unparalleled beauty. The redwoods and sequoias seem permanent, indestructible—yet they also issue a warning about a vulnerable future.

Christopher Johnson is a writer specializing in conservation, forestry, and history. He wrote *This Grand and Magnificent Place* (University Press of New England, 2006) and, with David Govatski, *Forests for the People* (Island Press, 2013). Johnson is a frequent contributor to *Appalachia*. Visit him at chrisjohnsonwrite.com.