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An Emerging Triad: Air Pollution, Beetles, and Wildfire

Victoria Minnich

Pine mortality near Lake Arrowhead in 2003.

Tree Signals and Beetle Outbreaks

Biochemical changes in trees stressed by drought and air pollution may attract bark beetles, which overwhelm the trees' defense mechanisms.

In the past decade, bark beetles have killed millions of acres of trees across the West. Environmental stresses like prolonged drought and increased air pollution are important factors driving the massive beetle outbreaks. Besides triggering a protective process within trees, these stresses may also exacerbate beetle attacks and add to wildfire fuel loads.

When a tree experiences extreme drought — drought lasting several years or more — its biochemistry begins to change. These biochemical changes may actually signal beetles that a tree is stressed and ultimately attract more beetles than the tree can tolerate. An overwhelmed tree often translates to a dead tree and provides a staging area for future beetle generations. Understanding the process of stress signaling and beetle response will provide important information for forest management in a changing climate.

Nancy Grulke, a plant physiologist based in Riverside, California, with the Pacific Southwest Research Station, is studying how drought is translated to bark beetle signaling by looking at resin production of Jeffrey pine trees in six similarly aged stands spread across the state. She's leading a team of entomolo-gists (Steve Seybold, U.S. Forest Service and Andy Graves, University of Califronia, Davis) and biochemists (Barbara Demmig-Adams, William Adams, and Kesanapalli Krishnaveni,

From Science…

- Chronic exposure to high levels of common air pollutants like ozone and nitrogen oxides is damaging to forest health. The effects of air pollution mimic drought and have the potential to increase fuel loads in forests, exacerbating the risk of wildfire, especially near urban centers where air pollution is more concentrated.
- When Jeffrey pine trees are stressed by drought, they send biochemical signals that may be an attractant to bark beetles. Since the signaling trees are already significantly stressed, they are easily overwhelmed by beetles, setting the stage for an outbreak. The same biochemical signaling may also happen in other important forest species.
- Stand density appears to influence tree mortality during periods of drought and beetle outbreaks.

University of Colorado) in this investigation. At her study sites, Grulke made a series of pencil-diameter holes through the craggy outer bark of the tree. The holes are about chest-high off the ground and just barely pierce the cambium, or the living tissue right under the bark. The cambium samples are assessed for their cell turgor—the pressure of a cell membrane against a cell wall—that provides important information about a tree's ability to exude resin.

Daniel McGlynn

When a tree is in good health, resin will ooze from any nicks in its bark and provide a physical barrier to burrowing bark beetles. Stressed trees do not produce as much resin as healthy trees.

The sweet-smelling resin in a Jeffrey pine is an indicator of the tree's overall health. If the tree is healthy, a steady stream of resin will slowly ooze from a wound, like clear candle wax. If it is rusty looking, or contains bits of sawdust-like material called frass, then the tree may be infected with beetles. If the tree is stressed, or drought stricken, resin production can drop, and the tree will be unable to physically ward off the bark beetle.

Besides changing a tree's chemistry, prolonged drought can also have physical consequences. One thing that happens is that different tissues of the tree lose turgor pressure. This pressure is critical to overall plant growth and function, but also plays a significant role in forcing resin to a point of beetle entry. A healthy tree, with good turgor pressure, may be able to fend off invading beetles with resin. A drought-stricken tree will have a harder time. Declining pressure may also cause a tree to self-prune, or drop needles and branches. This leaf litter adds to the fuel load of an already dry forest, exacerbating concerns about wildfire.

The importance of understanding drought signaling and beetle response goes beyond Grulke's handful of study stands. The drought-beetle complex is not only being repeated across the West, but across the world. "It's a single unifying theme," says Grulke, about the increasing forest disturbance regime. ■

Daniel McGlynn

A study site in a stand of Jeffrey pine in the San Bernardino National Forest.

Environmental Stress: Air Pollution and Forest Mortality

The San Bernardino Mountains, which help define the Los Angeles Air Basin, are one of the most polluted mountain ranges in North America. The air pollution is the result of a combination of emissions from vehicles, industrial manufacturing, and agriculture production. These greenhouse gas emissions, ozone and nitrogen oxides in particular, are especially damaging to forest health.

Increased ozone and nitrogen deposition change the chemical composition of individual trees and have significant impacts on fuel loads at the stand and forest level. Inside the leaf, ozone changes the way trees transpire, or exchange gasses. Leaves, or needles in the case of conifers, have pores called stomata. Properly functioning stomata are crucial to a tree's ability to regulate water loss, uptake carbon dioxide, and produce energy. In the presence of high concentrations of ozone, trees lose stomatal control and the ability to manage their water and nutrition. Too much air pollution can kill a tree outright. But what's more likely, with high but not excessive exposures to ozone, is the slow dwindling of health. Since water is lost from the tree, the results of chronic ozone uptake mimic or exacerbate tree drought stress.

Nitrogen deposition is also a problem facing forests. Some nitrogen is generally good for trees, but too much nitrogen can change the amount of growth, the timing of growth, and resource allocation within the tree that can compromise its health and ability to withstand stress. Working in concert with ozone, increased nitrogen may affect the way carbohydrates—the energy needed for growth and survival—are stored and used, and stunt root growth. These two factors can also make a stressed tree much more susceptible to drought and its follower—beetle outbreaks.

Both ozone and nitrogen deposition cause increased leaf turnover and self-pruning, which lead to more litter on the forest floor. Nitrogen deposition also acts to slow the decomposition of forest floor litter, particularly the excess branches and leaves being shed. As a result there is a potential to have more fuel in a drying forest, enhancing the potential for catastrophic wildfires.

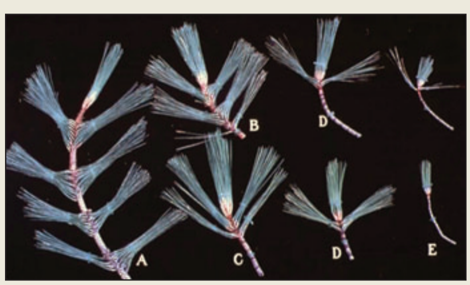
Sequoia-Kings Canyon National Park

Summer ozone levels in the western Sierra Nevada are 67 parts per billion (ppb)—up from 10 to 12 ppb in preindustrial times.

Nancy Grulke has been studying the effects of air pollution on forest health for the past two decades for the Pacific Southwest Research Station. Her research reveals links between high doses of ozone and nitrogen to forest stress, and shows there is a compounding relationship between stressed trees, beetle outbreaks, and wildfire.

Air Pollution in the Background

Thanks in large part to regulation and education in past decades about air pollution in the Los Angeles Air Basin, sources of pollutants are now better controlled. On any given day, there is less air pollution being emitted than there was a decade ago.



Anthony Gomez

Air pollution inhibits tree growth. Above are samples of ponderosa pine taken from a clean site (A) and a range of polluted sites (B through E).

The problem though is that the overall dose is steadily climbing, not only around Los Angeles, but across the globe. The current atmospheric background rate of ozone is 50 parts per billion (ppb), up from 10 to 12 ppb in preindustrial times, and it is expected to increase another 50 percent between 2020 and 2050. "We have continuously increasing ozone," says Grulke. Pollution is worse in some places than others, for example, downwind from large urban areas. But even forests far from urban centers are showing higher levels of ozone. The Sierra Nevada, generally synonymous with clean mountain air, now has a background rate of 67 ppb during the summertime when plants grow.

"We're dealing with completely different atmospheric chemistry," says Grulke, "when ozone is greater than 70 ppb, stomata function very differently than they do when ozone is 50 ppb." At some of her study sites of ponderosa pine scattered throughout the San Bernardino Mountains, the rates of summertime ozone uptake ranged from 62 to 80 ppb. The higher ranges are closer to urban Los Angeles, whereas the lower exposures are farther east, out toward the Mojave Desert.

The study site with the highest ozone levels is a place called Camp Paivika in the San Bernardino National Forest. In the early 2000s, this area experienced a severe drought, followed by a beetle outbreak from 2003 to 2005 that killed 80 percent of the trees, and then a high-intensity ground fire. Now, two numbered survivors are all that remain of the original 180 study trees at the site.

This pattern of drought stress, compounded by air pollution, followed by beetles, and culminating in wildfire, is potentially an emerging trend across the West. "We have more reason for the bark beetles," says Grulke, "and from the way things look, more wildfire too."

To better understand how ozone affects forest, Grulke built a piece of equipment that can monitor the amount of ozone "flux" in leaves of trees. The idea is to record the amount and duration of ozone exposure, monitor the tree's response, and then be able to quantify how much is too much ozone.

The Models

The effect of ozone and nitrogenous pollutants are often left out of climate models, which favor measuring and predicting the rise and consequences of increased carbon. Not quantifying and including ozone and nitrogen in models, according to Grulke, may be a big oversight. Unlike some other greenhouse gasses, there is still little understanding about specific plant thresholds of ozone and what happens after that threshold is exceeded. Besides ponderosa pine, Grulke has also measured the tolerance in a handful of other plants and trees, but a wholesale cataloging of "what proportion of plants are in trouble," she says, is still lacking.

In addition to modeling, Grulke's research can also inform other forest management strategies, like thinning. At some study sites, she's looking at whether stand density plays a role in buffering the effects of air pollution and how those stands deal with the subsequent stress of drought and beetles.

The effect of air pollution on plant health is not just a forestry issue. In Europe, researchers are trying to figure out ozone tolerances for important agricultural products and certain types of heritage trees. "Air pollution is the one link that ties everything together," says Grulke. ■

…to Management

- Future predictions of tree, stand, or forest health will be stronger if a combination of environmental stressors like drought, ozone, and nitrogen compounds are considered. Currently, significant levels of ozone are not included in any carbon, biogeochemical, biogeographic, or hydrological models in the United States.
- Understanding what makes a tree susceptible to beetle attacks can aid future predictions and monitoring of stands and forests.
- Stand thinning may be a mitigation tool for areas affected by drought and beetle outbreaks.

Nancy Grulke

A thinning crown of Jeffrey pine in Sequoia National Park.

Nancy Grulke

Stands stressed by drought, air pollution, and beetle attacks are prime sites for wildfire.

Lisa Neal

Nancy Grulke.

Scientist Profile

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Nancy Grulke first started thinking about climate change and its impacts in the eighth grade when her math teacher presented the class with a chart that contained new data showing global increases in temperature and carbon dioxide concentrations. "The teacher asked the class 'to fit the curve and tell me whether the earth will get hotter or cooler,'" Grulke says. "It was 1970 and they really didn't know." Several years later, while studying botany at Duke, a professor suggested that Grulke pick a tract of subalpine forest and keep tabs on it for the rest of her career, a sort of lifelong longitudinal study to document a place as it changes. When asked how the study is going, she says, "give me another 30 years, then I'll be able to tell you." The forest is filling in meadows near treeline, but the position of treeline hasn't changed much since 1977.

After getting a Ph.D. in botany from the University of Washington in 1983, Grulke studied the effects of drought in the polar desert, and then started researching the consequences of air pollution on forests in southern California. One of her main pursuits as a scientist has been to study the role of ozone, nitrogen deposition, and drought on forest health. Along the way, she built a piece of equipment that can measure specific thresholds of ozone on different species of plants. As the global level of ozone rises, this information will become increasingly important.

Now Grulke is the project leader of forest health and disturbance for the Pacific Southwest Research Station, and is based out of the Forest Fire Laboratory in Riverside, California. ■

A Conversation With Nancy Grulke

Q ***How can you tell if a forest is healthy?***

There are lots of indicators of forest health. Generally, the attributes that I focus on in my work are leaf production and longevity, the dimensions of the tree, branch growth, and the number and types of pathogens the tree is hosting. Some definitions of tree health are solely based on the presence of biotic and abiotic pathogens. In other words, a healthy tree means no presence of pathogens. I've found though, that if you look hard enough, almost every tree out there has some sort of disease. What matters are the other factors in the ecosystem that allow diseases to flourish and overwhelm the tree, and then become an issue at the stand or forest level.

Q ***What kind of role will air pollution play on future forest health?***

What we're seeing is a pattern of forest disturbance that starts with exposure to high concentrations of air pollution and ends with beetle outbreaks and wildfire. What's alarming is the frequency and repetition of this pattern across the landscape in the past decade. Beetles and wildfire are not just a problem in southern California, or the Western United States. The same pattern is repeated in other places too, like the Korean Peninsula and in Eastern Europe. When the level of atmospheric pollution rises, as it's expected to, these cycles of forest disturbance, fueled by air pollution, will be more intense.

Q ***How many plant species are affected by air pollution?***

Well, we don't really know. Using an instrument that I modified to measure ozone exposure on plants, I've looked at four important forest species in southern California: ponderosa pine, Jeffrey pine, California black oak, and blue oak. But I've also measured the effect of ozone on other trees such as European beech and Holm oak, a tree that grows throughout the Mediterranean and is similar to canyon live oak in California. Of these species, Holm oak is the only one that's tolerant to increased exposure to ozone. I'm also curious about the effects increased atmospheric pollution will have on agricultural crops. So far I've measured the ozone threshold of snap peas, sugar cane, and soybeans.

Q ***How has remote imagery aided the study of forest health?***

We've been using data obtained on the ground and combined that with data we've gotten from doing fly-overs with planes equipped with infrared and visible imaging systems. Working with Dr. Phil Riggan's imagery team (USFS), we can tell, based on the reflectance of wavelengths of light, what's happening in the forest. There are lots of variables in the way that a forest canopy reflects light; we can even tell different species apart from the imagery taken from the cameras mounted in the airplane. The thermal imaging can also tell us something about transpiration. This could be a powerful tool for looking at large tracts of forest across landscapes. It might give us insight into really stressed areas before they become problematic, and it will make continual monitoring easier.

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What's Next

The worldwide level of atmospheric air pollution is steadily climbing. In just a couple of decades it may reach levels in places where it becomes an overwhelming stress to forest health. To best understand impacts of air pollution, it's important that greenhouse gasses like ozone and nitrogen oxides be included in future climate models, at appropriate future levels. Modeling helps to inform management strategies, but without critical information about the role of increased pollution, these models may not accurately reflect the situation on the ground.

Now that the relationship between air pollution and other forest disturbance like disease and fire has been established, other plants' thresholds to ozone and nitrogen need to be determined. Understanding how different species tolerate air pollution is key to forecasting future forest health. This information will also help guide future management decisions and inform forest plans. Using technology like thermal and infrared imaging will also help with forest stress monitoring and predicting beetle outbreaks and mortality. ■

Writer's Profile: Daniel McGlynn is a California-based journalist who covers topics relating to science and the environment. His work has appeared in local, regional, and national publications.

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For Further Reading

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