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Science FINDINGS

INSIDE

"Science affects the way we think together."
Lewis Thomas

Hot Air or Dry Dirt: Investigating the Greater Drought Risk to Forests in the Pacific Northwest

Researchers install a study plot to monitor soil moisture on the steep, north-facing slopes of Watershed 1 in the H.J. Andrews Experimental Forest in western Oregon. Photo courtesy of Lina DiGregorio.

IN SUMMARY

Elevation, soil composition, and depressions can influence the distribution of water belowground and its availability to tree roots. During the summer months when precipitation levels are at their lowest, this belowground soil moisture can stave off the effects of drought stress on trees. Although lack of soil moisture is the most well-known driver of drought stress, it may not be the only driver.

Working in the H.J. Andrews Experimental Forest in western Oregon, researchers investigated whether a lack of soil moisture or warm dry air is the primary cause of the drought stress exhibited by trees in the study area. Using soil moisture measurements, tree cores, and the Soil-Plant-Atmosphere model, the team explored how tree growth is affected by the interactions of soil moisture and vapor pressure deficit. Vapor pressure deficit (VPD) is the drying power of the atmosphere and results from the combination of air temperatures and the amount of water vapor in the air.

The researchers found that even when soil moisture is available, trees experienced drought stress when VPD was high; this stress resulted in measurable decreases of latewood (summer) growth. Additionally, increases in VPD decreased tree growth more than decreases in spring and summer precipitation. This finding has long-term implications for forest productivity in the Pacific Northwest, where climate change is expected to increase summertime VPD.

"Hot, cold, moist, and dry,
four champions fierce,
Strive here for mast'ry."

—John Milton, poet

More than 44 miles of streams flow through the Lookout Creek watershed in the 15,700-acre H.J. Andrews Experimental Forest. For more than 70 years, researchers have collected data on precipitation, temperature, humidity, and streamflow to better understand how water cycles through this forested watershed.

Belowground processes in the water cycle, however, are less understood, yet no less crucial to supplying water during the summer months when trees and aquatic species need it the most.

Steve Wondzell, a research ecologist with the USDA Forest Service Pacific Northwest Research Station, has spent the better part of his career studying the interactions between the above- and belowground water-cycle processes.

In the Lookout Creek watershed, Wondzell saw an opportunity to build on decades of prior research to learn more about the cause of tree water stress—warm dry air or dry dirt—and how it affects trees. This fundamental information is key to understanding how trees are likely to respond to warmer summer temperatures and drier soil caused by climate change, as well as thinning treatments designed to reduce forest fuels.

Wondzell was initially inspired by research conducted on the Tenderfoot Creek Experimental Forest in central Montana. There, he worked with researchers from Montana State University who studied the effects of topography on how water moves through a watershed, specifically looking at the connectivity of hillslope hollows to streams.

Wondzell describes a hillslope hollow, which ranges from 65 to 165 feet in width, as “a little valley that runs up the side of a hill, except that it’s such a tiny depression in the hillslope that there’s not even a stream channel.”

KEY FINDINGS

- Contrary to expectations, in Watershed 1 in the H.J. Andrews Experimental Forest, hillslope hollows did not have higher soil moisture content than adjoining ridgetops. Soil properties, especially rock content, appeared to explain the observed soil moisture patterns.
- Latewood (summer) growth of 50-year-old Douglas-fir trees was strongly correlated to mean daytime vapor pressure deficit between June and July. This suggests that increases in summertime vapor pressure deficit are likely to reduce latewood growth and increase water stress in Douglas-fir growing in the Pacific Northwest.
- Modeling showed that increases in vapor pressure deficit decreased tree growth, or gross primary production, more than decreases in spring and summer precipitation. Atmospheric water demand, not soil moisture availability, appears to be the primary cause of tree water stress in the late summer. Temperature-driven increases in vapor pressure deficit from climate change are likely to reduce forest productivity regardless of soil moisture availability.

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The team found that the largest hillslope hollows had the largest hydrological connectivity to streams and accounted for most of the streamflow. The research was extended to the Lubrecht Experimental Forest in western Montana, and they found that hillslope hollows also stored more belowground water. The trees growing in these hollows were also more productive and exhibited signs of less water stress.

Wondzell wondered if these observations held true at the H.J. Andrews. He installed a few wells in some hillslope hollows, but the wells never went deep enough to strike water. When funding to further this work became available through the H.J. Andrews’s Long-Term Ecological Research program for research on soil moisture availability, he seized on the opportunity.

“There’s a lot of interest in soil moisture availability because people are concerned about tree water stress,” Wondzell explains. “Under climate change, will that water stress change or worsen?”

If hillslope hollows dependably provided a source of soil moisture during the summer when trees are most vulnerable to drought stress, forest managers could capitalize on that information. For example, in forest stands managed for timber production, foresters could prioritize retaining trees in these hillslope hollows and thinning the adjacent ridgelines.

Wondzell worked with Kevin Bladon, an associate professor at Oregon State University, to recruit Karla Jarecke to pursue this research for her PhD; in 2016, she set out to find out how hillslope hollows functioned in the H.J. Andrews Experimental Forest.

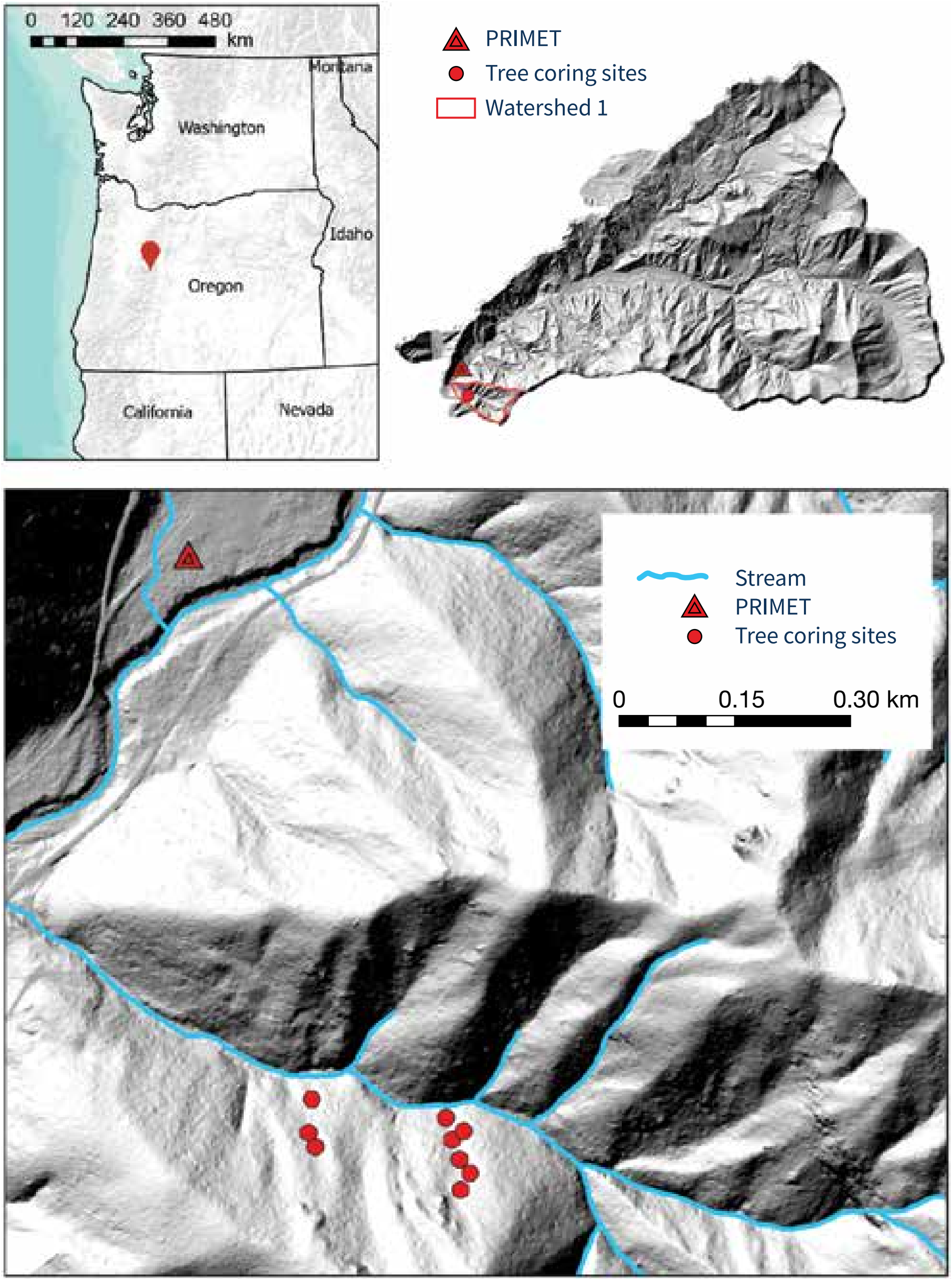
Water Behaving Unexpectedly

With its Douglas-fir-covered hillside that sloped on average 37 degrees to the stream on the valley floor, the rugged terrain of Watershed 1 was a difficult site to traverse for data collection. Jarecke recalls spending July 2016 hiking across steep slopes and around downed trees left by a timber harvest 50 years earlier to install 54 permanent soil water monitoring sites in the watershed.

Even the soil wasn’t cooperating. There were “so many rocks,” she says. Every time Jarecke and Aaron Rachels, an incoming master’s student also attending Oregon State University, inserted a 2-foot-long, stainless-steel rod into the soil, there was a good chance it would bend from hitting rocks below the surface.

After the sites were installed, Jarecke visited them 18 times between August 2016 and October 2017 to measure the amount of

Researchers collect information about the soil profile in Watershed 1 in the H.J. Andrews Experimental Forest. Photo courtesy of Karla Jarecke.



The H.J. Andrews Experimental Forest study area. Researchers used long-term climate records from the PRIMET (primary meteorological) station, soil moisture measurements, soil samples, and tree cores to determine if there was a connection between tree growth and two sources of water stress: precipitation drought and atmospheric dryness.

moisture in the soil. This meant lugging a large, square, 30-pound piece of equipment (a time domain reflectometer) up and down the slope. She also installed 10 additional sites for data loggers that collected soil moisture every 30 minutes, which she visited monthly to replace batteries.

In the summer of 2017, Jarecke did a preliminary analysis of the soil moisture data. “We were actually finding that less water, on average, was stored in the hollows than on the adjacent ridges,” she explains.

“This relationship is backward to what we expected; soil moisture patterns appeared to be controlled by something we didn’t measure,” adds Wondzell.

The team wondered about the differences in soil properties on the hillslope as an explanation for what they were observing. To learn more about the belowground properties, they measured the depth to bedrock at 38 of the 54 sites. This meant lugging to each plot 70 pounds of solid steel rod segments that, when screwed together, formed a knocking pole. The knocking pole was used to measure the depth from the land surface to fresh bedrock, which provided information on the belowground water storage capacity.

Jarecke also collected soil samples at 13 of the 54 sites. The soil samples confirmed not only the rockiness of the soil but also the earlier conclusion: the hillslope hollows were drier than the ridges. The analysis suggested something else as well. Although the hillslope hollows were drier, soil moisture was still present in the soils that were nearly 9 feet deep, on average.

“How in the world can the trees be water stressed if they haven’t used all the water available in the soil?” Wondzell recalls pondering.

“We spent a lot of time at the whiteboard asking ourselves, ‘Is this data actually correct?’” recalls Bladon.

Rethinking Drought Stress

In 2018, Jarecke read up on other studies that researched why trees might experience drought stress. What she learned was that the drought stress could be coming from aboveground. “New studies were emphasizing the impact of increasing vapor pressure deficit on tree water stress,” she explains. “And there’s a misconception in forest management on how we’ve been thinking about water stress being all about the belowground drought stress.”

Jarecke describes vapor pressure deficit (VPD) as the “drying power of the atmosphere” or phrased another way, how much water vapor or humidity is needed to saturate the air at a given temperature. Hot air can hold more moisture than cold air, which means as temperatures increase without a corresponding increase in humidity, VPD increases.

So, how does VPD affect trees?

“You can think of a tree as a cluster of tiny straws,” explains Wondzell. “As the soil dries out, the tree finds it harder and harder to pull soil water into the bottom of these straws. Conversely, aboveground it is the dryness of the air that does the pulling. And as the air gets drier, it pulls harder and harder on the water at the top of the straws.”

This band of tiny straws is located underneath the bark and is called the xylem. Xylem are overlapping hollow dead cells that can be about 1/8-inch long. Tiny pores connect the dead cells to create a continuous column of tiny straws that run from the roots up to the needles. Eventually, if a column of water is pulled too hard from either end, it can break, forming an air bubble inside the cell and creating an embolism.

In conifers, such as the Douglas-fir growing in Watershed 1, if embolisms occur in too many of the xylem cells, the tree will struggle to transport enough water from the soil to the needles. And if the water stress gets too great, the tree will experience runaway embolisms and die. Trees have strategies to protect themselves from embolisms, but these protection strategies come at a cost.

To test whether VPD could be the explanation, Jarecke took two complementary approaches. For the first approach, she used the Soil-Plant-Atmosphere model to test the response of Douglas-fir's primary growth rate, or productivity, and transpiration to increased VPD and decreased precipitation from March to August.

Within the model, Jarecke could simulate different weather scenarios, such as holding precipitation constant while increasing VPD, or holding VPD constant and decreasing precipitation throughout the year. "It's a controlled experiment to tease apart how the two factors affected the Douglas-fir growth," she says. What the results showed was that decreases in spring and summer precipitation had less of an impact on gross primary production than increased VPD.

"The trees' gross primary productivity would decrease by about 2 percent with the change in precipitation expected from climate change, while the projected increases in temperature would tend to decrease the gross primary productivity by about 7 percent," explains Wondzell.

For the second approach, Jarecke used the tree's internal record of drought stress that can be found in its tree rings. This meant revisiting the plots, this time collecting core samples from three dominant trees at each plot. Of course, science is never simple and collecting core samples in the field in the fall of 2019 proved challenging. Throughout Watershed 1, even more trees had been brought down by a snowstorm in February 2019. "Navigating around those newly fallen trees was challenging," Jarecke recalls.

In the lab, she processed the core samples to determine the ratio of ^{13}C to ^{12}C, two stable, nonradioactive carbon isotopes in atmospheric carbon dioxide (CO_2). When the tree is water stressed, there is proportionally more of the ^{13}C isotope present, relative to the dominant ^{12}C isotope, in the latewood that trees typically produce during mid-summer.

This results from a tree's self-protective measure of closing its stomates to prevent water loss. The closed stomates limit the new CO_2 entering the needles. CO_2 containing the lighter isotope, ^{12}C, is used more quickly in photosynthesis. When the stomata are closed, ^{12}C is drawn down and a greater amount of ^{13}C is used compared to when the stomata are open to the atmosphere. Thus, the ratio of ^{13}C to ^{12}C can be used as a measure of the amount of water stress experienced by the tree.

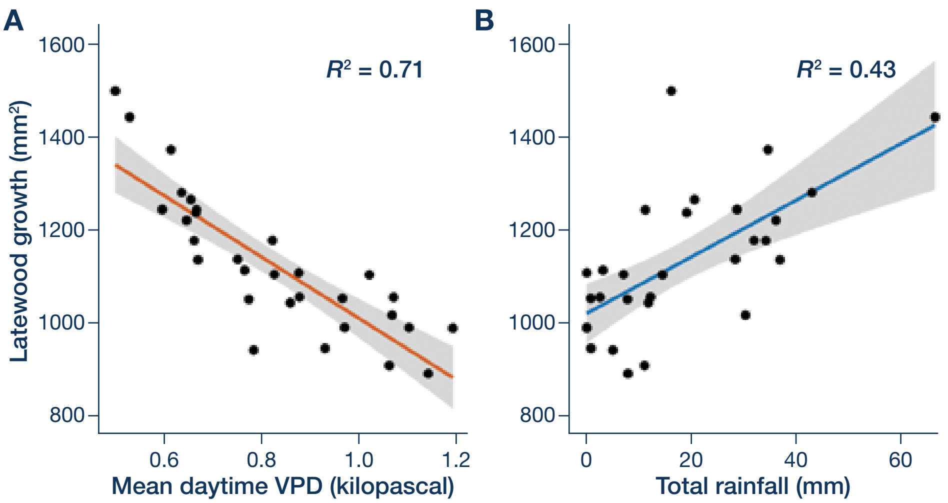
Using a statistical technique called Climatic Window Analysis and daily weather data from 1999 through 2019, Jarecke compared the latewood growth and carbon isotope composition to all possible climate windows with lengths spanning from a single day to many months over the preceding year to see if there was any relationship.

Wondzell describes this analysis method as "a brute force technique of looking at every possible period of time." In this case, he adds, it seeks to answer the question: "Is the amount of latewood growth related to the weather on the 31st of May, or related to the weather over the last two weeks of May, or the weather over the months of April and May combined?"

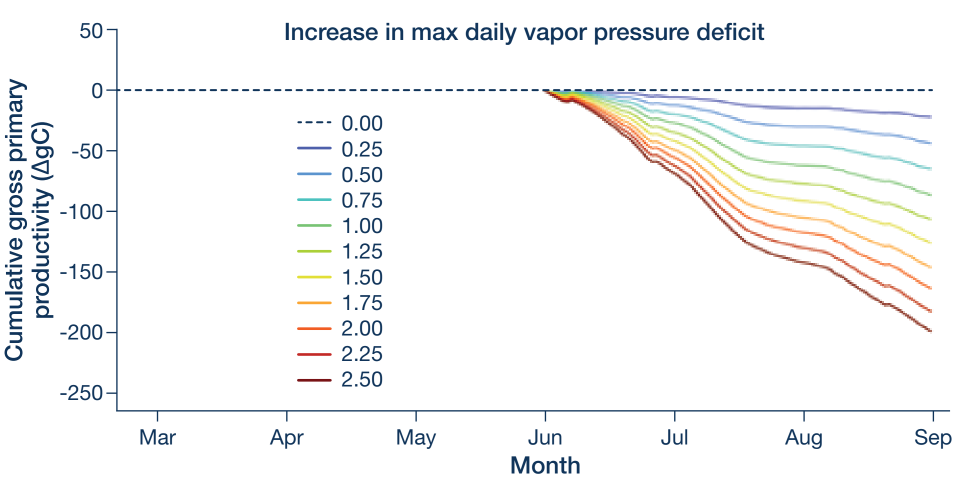
Latewood carbon isotope composition was most strongly correlated to mean daytime VPD between May and September and total rainfall between May and August. The researchers noticed that increased VPD during June, when there was still plenty of soil moisture, decreased the latewood growth, which lent weight to the hypothesis that VPD limits growth even when soil moisture is plentiful.

In reflecting upon the results, Jarecke says that she was surprised that the timing and amount of rainfall did not appear to have a strong influence on latewood growth; however, this may be because Watershed 1 is a north-facing slope with deep, silty, clay loam soils capable of holding water late into the growing season.

"The collection of Karla's research strongly suggests that at her study site, these trees are highly sensitive to vapor pressure deficit," Wondzell says. "Of course, they're also sensitive to rainfall, but it's actually vapor pressure deficit that is by far and away the bigger driver."



Researchers analyzed 30 years of tree ring data and found that both increased vapor pressure deficit (VPD) and decreased rainfall led to decreased latewood growth. However, latewood growth was more strongly influenced by increasing vapor pressure deficit than by decreasing late-spring and early-summer rainfall.



Model simulations showed that tree growth (denoted as gross primary productivity) declined as the vapor pressure deficit increased. Global climate change models project that air temperatures will increase between 2 to 9 °F by 2070 in western Oregon according to moderate climate change scenarios. These temperature increases will correspond to a 0.25 to 1.0 kilopascal increase in vapor pressure deficit, and a 3 to 11 percent decrease in gross primary productivity (average = 7 percent).

LAND MANAGEMENT IMPLICATIONS

- Although patterns in soil moisture availability were present at the hillslope scale, the spatial patterns in soil properties that create them are currently impossible to map accurately at landscape scales. Consequently, there is no easy way to use these patterns to inform silvicultural treatments.
- The sensitivity of Dougals-fir water stress to vapor pressure deficit has critical implications to managing forests of western Oregon for drought resiliency in a changing climate. Hotter summer temperatures expected from climate change are likely to drive higher vapor pressure deficit and exacerbate water stress in the future.
- If vapor pressure deficit is a primary cause of water stress and a primary limitation to tree growth during the long, dry summers typical of western Oregon, thinning could prove ineffective, or even counterproductive, for increasing drought resilience. Thinning a stand could allow penetration of hot, dry air deeper into the canopy, potentially increasing tree water stress.

Managing Future Forests?

This was a single study at one location, but its findings are intriguing and lead to additional questions, the answers to which could help forest managers design treatments for warmer, drier conditions.

"With projections calling for a warmer, drier atmosphere in the future, it's really important that we get a handle on how tree species in the Pacific Northwest will respond to those changes, both in a warmer, drier atmosphere, but also with reduced amounts of water in the soil," says Bladon.

"Considering the results of this research and the fact that we think increases in VPD are unavoidable across the Pacific Northwest in the future, how can land managers think about the microclimate of the stand?" Jarecke says. "We really don't know how the different ways that managers cut forests are impacting the microclimate."

On the Nisqually Community Forest in Washington State's Pierce County, tree cutting has occurred since 2015, both to improve forest health and to experiment with creating snow gaps that could accumulate more snow and increase summer water availability to nearby streams. Jaal Mann, lead forester with the Northwest Natural Resource Group that helps manage the community forest, says learning that VPD could potentially be a cause of drought stress is interesting.

"I'd be very curious to see future research measuring VPD in the lower canopy of thinned stands to see how different densities of thinning can affect VPD and, by extension, the trees," he says. Nisqually Community Forest land managers see light availability as the main stressor on trees, but that may change in coming decades as the climate warms.

The silviculture treatments that Mann designs for landowners typically plan for treatments occurring about 15 to 20 years apart. This timing reduces thinning costs and equipment impacts on the soil. However, "if vapor pressure deficit does impact drought stress in our sites, and thinning is found to increase vapor pressure deficit in the canopy, that could make us do more frequent, lighter entries to reduce its effect," Mann explains. "There can be a variety of reasons why landowners wouldn't want a lot of entries; but if vapor pressure deficit does become an issue, that could be something we rethink."

Mann is not alone in recognizing that management activities may have to be reevaluated. A takeaway for Wondzell is that "we can't just think about the soil," he says; "we have to think about the atmosphere. We have to rethink everything we know about how trees grow across the landscapes."

Writer's Profile

Andrea Watts is a freelance science writer based in the Pacific Northwest. Her portfolio is available at https://www.wattsinthewoods.com, and she can be reached at andwatts@live.com.

The thirsty earth soaks up the rain,
And drinks, and gapes for drink again.
The plants suck in the earth, and are
With constant drinking fresh and fair.

—Abraham Cowley, poet and essayist

For Further Reading

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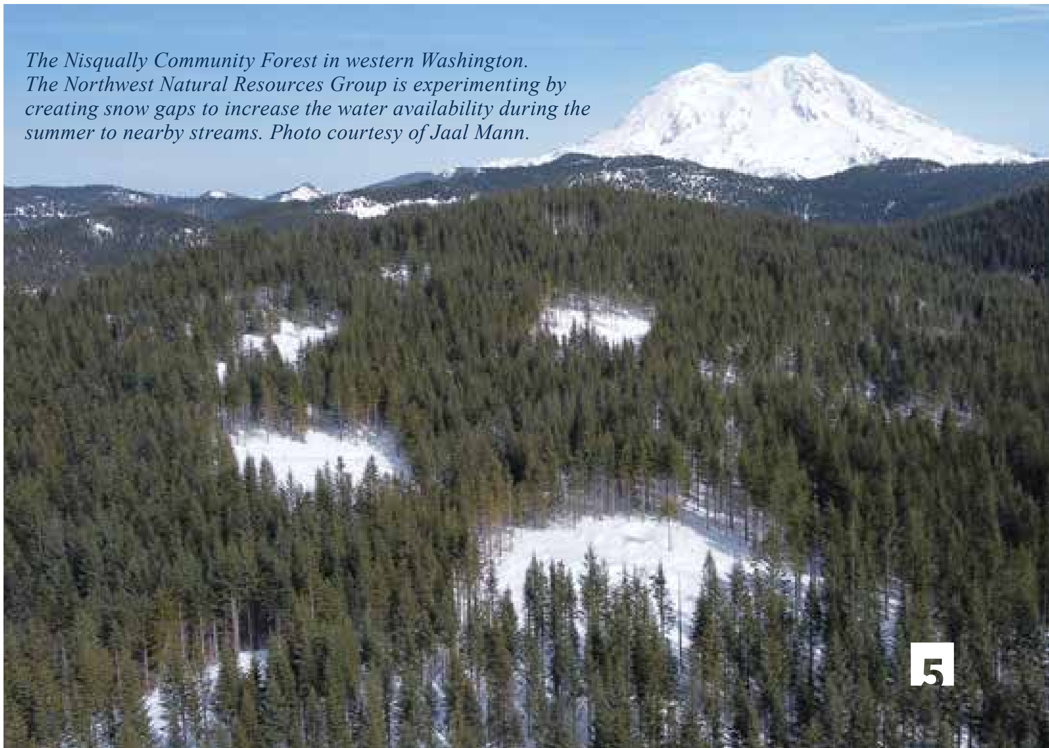

The Nisqually Community Forest in western Washington. The Northwest Natural Resources Group is experimenting by creating snow gaps to increase the water availability during the summer to nearby streams. Photo courtesy of Jaal Mann.

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