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Eos

SCIENCE NEWS BY AGU

THE SCIENCE OF RESILIENT FORESTS

Researchers develop tools and techniques to monitor and preserve woodland health.

MESSENGER Reveals a Mercurial Mercury

An Inclusive Approach to Oceangoing Research

Supercontinents and Mantle Structures

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Mentoring365 Circles

Join these peer-group learning environments!

Mentoring365 Circles officially launches in January 2023!

In 2022, more than 150 members participated in three trial Circles on **Careers Outside Academia, Science Communication** and **Pre-Conference Science Networking**.

What is a Circle?

Circles are groups of peers who meet around a shared interest to learn from one another. Depending on the size of the Circle, some groups will be discussion based while others will function like online workshops. Each Circle is facilitated by a lead member who is responsible for creating a plan, fostering engagement among members, and ensuring the group achieves its goals.

How does a Circle work?

Members of a Circle can discuss topics on the Mentoring365 platform, organize virtual meetings, create goals, share resources, and connect with one another to expand their network.

How long does a Circle last?

A Circle can last anywhere from a few weeks to a few months, depending on the topic. Members can also adjust, extend, or even repeat a Circle, based on interest and time.

Who can lead a Circle?

Anyone interested in connecting others around a topic can start their own Circle. Mentoring365 admins are available for technical support and issues that may arise.

What is the time commitment for Circle Leads?

The commitment is based on the type of activities they plan to engage members in. Some Circle leads created discussion posts every other week for 3 months. Another Circle lead had one virtual presentation each month and posted follow-up discussion prompts based on those meetings.

Ready to join a Circle?
Go to mentoring365.chronus.com to sign up.

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A Forest, for the Trees

This month, *Eos* takes a walk in the woods to explore how forests are faring and what strategies are helping to strengthen our approaches to fire ecology.

In "For Western Wildfires, the Immediate Past Is Prologue," Ronnie Abolafia-Rosenzweig, Cenlin He, and Fei Chen strike an appropriately Shakespearean chord when noting that "the tight coupling between climate and fire in the western United States has been enhanced by the legacy of fire suppression and a lack of prescribed burning" (p. 28). Throughout this issue, scientists, historians, and policymakers echo this scrutiny of the long legacy of fire suppression in the U.S. West. They also work to address it: In this article, authors use burgeoning possibilities offered by satellite observation and machine learning to uncover the extent of burned areas and produce more accurate forecasts of summer fire activity.

Scientists studying refugia—those elusive patches of forest that evade incineration—are similarly researching ecosystems made unpredictable by human activity and climate change. "Last Tree Standing" by Robin Donovan documents how scientists analyze the seemingly arbitrary distribution of forest refugia and use tools ranging from seed-dispersal databases to Traditional Knowledge frameworks to predict and preserve them (p. 22).

Finally, by taking "A Lidar's-Eye View of How Forests Are Faring," scientists use a familiar and flexible technology to reveal a holistic portrait of forested landscapes (p. 34). Van R. Kane, Liz Van Wagtendonk, and Andrew Brenner provide dazzling lidar images of Yosemite National Park while detailing how such data are not limited to fire management applications.

In addition to these deep dives out West, this month offers introductions to Free-Air CO_2 Enrichment technology in the Amazon (p. 4) and the Internet of Things in Germany's Black Forest (p. 18). We hope this issue of *Eos* offers you some practical hope by way of solutions-oriented approaches to wildfire ecology.

Caryl-Sue Micalizio, Editor in Chief

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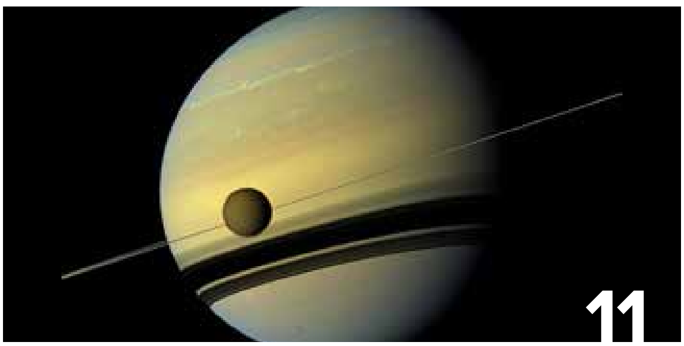
Features

On the Cover

A fire encroaches on a forest near Cherskiy, Russia, in 2020. Credit: Nikita Zimov



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Testing the Resilience of the Amazon

Hang on to your seats: An international project is preparing to intentionally release carbon dioxide (CO_2) into patches of the Amazon rain forest to understand how such ecosystems will respond to climate change. It may sound counterproductive, but the experiment will help answer an elusive question: Will the biggest tropical forest in the world continue to soak up carbon from the atmosphere as temperatures continue to rise?

With more than 20 years of planning and some $5 million in funding from science agencies in Brazil and the United Kingdom, AmazonFACE (Free-Air CO_2 Enrichment) will use 35-meter-high metal towers to inject CO_2 into the tree canopy at a forest research station in Manaus, Brazil. Scientists have conducted similar experiments using FACE technology in forests in Australia, Italy, and the United States, but this is the first time FACE will be deployed in a tropical environment.

The annual amount of CO_2 to be injected into each plot (about 1,200 metric tons) is the equivalent of the carbon footprint of a single round-trip flight from New York to São Paulo, said scientists. The amount of CO_2 emitted by the towers will be offset through reforestation, largely in the region outside Manaus.

"This is a fundamental experiment," said Jerry Melillo, a biologist at the Marine Biological Laboratory at the University of Chicago who is not involved with the initiative but tried to raise funding to conduct a similar experiment in the Amazon 2 decades ago.

"The tropics have been a big question mark," he explained, in understanding forests' carbon sink capacity in a high-emissions future. Today forests sequester about a quarter of all CO_2 emitted by humans.

Carbon Sink or Carbon Source

For more than 30 years, scientists have discussed what will happen to forests as CO_2 in the atmosphere continues to rise.

In theory, plants grow faster when exposed to increased amounts of the gas: Trees take up CO_2 from the air through photosynthesis and transform it into sugars that may add to their biomass. Some researchers have hypothesized that great amounts of CO_2 would therefore "fertilize" forests, allowing them to continue to absorb carbon and slow climate change—and that is what research using FACE in nontropical forests has suggested so far.

But critics have argued that this process might not apply to tropical forests because they have soils poor in nutrients, which would limit plant growth at some point. In a warming climate, tropical forests could start releasing more CO_2 through respiration than they absorb through photosynthesis, making them carbon sources instead of carbon sinks and further accelerating climate change.

"This will be the most precious carbon ever emitted in the Amazon. It will help us understand and preserve the forest."

The AmazonFACE project, as shown in this artist's illustration, will involve a series of 35-meter-high metal towers injecting CO_2 into the tree canopy. Credit: P. Lorenzo & R. Lupo/AmazonFACE

"We currently don't know how long this fertilization effect can be sustained or if it is even real," said David Lapola, leader of the AmazonFACE project and an ecologist at the University of Campinas in Brazil. Lapola pointed out that under a carbon-saturated environment with extreme climate change, the Amazon could become a dry and hot savanna. "That [situation] would bring catastrophic changes that would alter the climate on a continental scale," he added.

Recent studies have suggested that the Amazon has already lost more than 30% of its ability to soak up carbon since 1990. Lapola said it is not possible to know yet whether this is due to changes in climate. The new experiment will help answer this and other questions.

Pumping Gas into the Forest

The AmazonFACE project has a long history. The original idea was proposed in the 1990s, and work on the current iteration began in 2011. But lack of funding and logistical challenges got in the way. "Can you imagine producing all these giant towers and bringing

A researcher ascends an observation tower in a plot near Manaus, Brazil, where the AmazonFACE experiment will be carried out. Credit: João M. Rosa/ AmazonFACE

a giant crane into the dense forest?" asked Lapola.

AmazonFACE will involve a series of towers arranged in six 30-meter-diameter rings in the rain forest. Each ring will contain 16 individual towers. Two plots are currently under construction, and the remaining will be ready by late 2023, when the experiment starts running.) Half of the rings will pump out 50% more CO_2 than is currently in the atmosphere; the rest will serve as controls and spray only regular air.

Sensors in the towers will record the temperature and the concentration of water vapor and CO_2 in the air. Monitoring will go on for the 10 years that CO_2 will be emitted from the towers, during which time researchers will also measure characteristics of the forest including leaf and root growth; the amount of carbon in the plants, soil, and air; soil nutrients; the rate of photosynthesis; and water flux. These measurements will help researchers better understand how the trees use carbon, and results will be shared with local communities and policymakers.

"The big question is, Where will the carbon go?" asked Richard Norby, an ecosystem ecologist at Oak Ridge National Laboratory who is involved with AmazonFACE. If the additional carbon does not increase wood growth, for example, it may increase the growth of leaves and roots, which can quickly return the gas to the atmosphere. "Even if there is no tree growth, there almost certainly will be some important responses that will improve our understanding of how the ecosystem will react."

"This will be the most precious carbon ever emitted in the Amazon," said Lapola. "It will help us understand and preserve the forest."

By **Sofia Moutinho** (@sofiamoutinhoBR), Science Writer

An Inclusive Approach to Oceangoing Research

The research ship leaving the port of Rimouski in August 2022 appeared to be embarking from the St. Lawrence River on yet another science expedition.

But this voyage was anything but ordinary.

The people on board included artists, social scientists, members of a nearby Indigenous community, and (a few) scientists. Many identify as part of groups that have traditionally been minoritized in the marine sciences. And most had never done anything like this before.

Led by Réseau Québec Maritime (RQM), an oceanographic network hosted by the University of Quebec at Rimouski, the Inclusion Mission would take the group northeast along the secluded north shore of the St. Lawrence River and Gulf of St. Lawrence. In the days to come, they'd not only trap sediment, trawl for ocean life, and record the water's physical and chemical characteristics but also make art and meet with Indigenous communities.

Although the trip constituted only one of many research cruises worldwide, it built on movements to decolonize science and make discovery accessible to all.

For one of the Inclusion Mission's attendees, postdoctoral scholar Annie Tamalavage, early feelings of imposter syndrome on the cruise transformed into feelings of belonging by the trip's end. "It was like a very, very profound experience," she said.

A Seat at the Table

The goal of the Inclusion Mission, said trip leader Maxence St-Onge, was to break down barriers to seagoing research.

A marine geologist by training, St-Onge conducted a diversity analysis of RQM voyages in early 2021. Despite the organization's best efforts, the sea expeditions had low diversity, equity, and inclusion of women, racialized minorities, Indigenous Peoples, people with disabilities, and people identifying as LGBTQIA2S+. Trips lacked a variety of fields of study, too.

For one attendee, early feelings of imposter syndrome on the cruise transformed into feelings of belonging.

Many minoritized groups face barriers to participating in research cruises. Fewer than 30% of U.S. oceanographic expeditions between 2000 and 2014 had female chief scientists, according to one study. A quarter of Canadians have a disability, but some geoscientists have said the field sends a message that they aren't welcome. LGBTQIA2S+ scientists reported in a global survey that they are less open about their identities in the Earth sciences than in other disciplines. And of the 6,720 graduate students in geosciences, atmospheric sciences, and ocean sciences in the United States in 2018, only 860 (about 13%) were people of color.

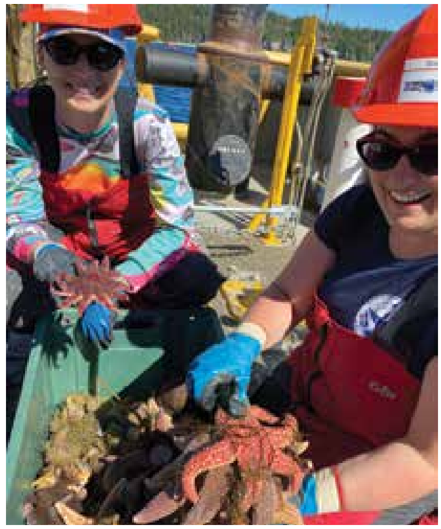
Calls to decolonize science have extended to oceangoing research, too. In 2019, the Canadian Indigenous Delegation summoned

Inclusion Mission participants worked together to create an art project inspired by oceanographic rosettes. Credit: Michel Castilloux the ocean-observing community to recognize the Traditional Knowledge of Indigenous Peoples worldwide. The Aha Honua declaration rallied scientists to create "meaningful partnerships" with Indigenous groups and nations.

To target these issues specifically, St-Onge prioritized applicants from minoritized groups or people from nontraditional research disciplines for spots on the cruise. And all participants took training from the Quebec-based, Indigenous-led training group Ashukan on best practices for research with Indigenous communities.

In the end, a little over a dozen people participated in the cruise, and each came with a unique story: An Innu intern had promised himself he'd try something new this year. An architect-turned-artist had regretted never having studied oceanography. And an early-career paleoclimatologist questioned her future in academia.

"I was just so hopeful and reminded [of] why I love this work in the first place."



Doctoral student Pauline Bertrand (left) and Réseau Québec Maritime scientific missions coordinator Maude Boissonneault show off the sea's bounty. Credit: Maxence St-Onge

William St-Onge: The Richness of the Sea

William St-Onge (no relation to Maxence) worked as an intern for the Territory and Resources sector in his Pessamit community along the St. Lawrence River's north shore.

When his supervisor told him about the Inclusion Mission, he immediately said yes. He'd promised himself to try new things that year.

On the ship, St-Onge dissected mollusks, released trawl nets, and scooped up sediment in a Van Veen sampler. These new tasks were part of research projects proposed by scientists who'd applied for the voyage. Working hours stretched from 7:00 a.m. to 11:00 p.m.

"There wasn't much I didn't like," said St-Onge. "Discovering all the marine life was stunning. I was clueless about most of it."

St-Onge also aided a research initiative involving five Indigenous communities and their changing relationship with the St. Lawrence. The research project is led by social scientist Roxane Lavoie from Université Laval in Quebec and seeks to understand how marine vessel traffic along the St. Lawrence River affects Indigenous communities.

During the voyage, Lavoie and others visited villages that could be reached only by boat or plane. Western science disciplines often choose research methods before starting a project, but Lavoie is cocreating the research design with her Indigenous partners.

Danielle Robitaille: A Place for Art

Artist Danielle Robitaille originally planned to study oceanography in college but chose architecture to stay closer to family. Although excited to finally go to sea, Robitaille worried about fitting in.

"I was a little afraid that art processes could be regarded as nonvalid by scientists, but that was not the case at all," Robitaille said.

Since 2019, Robitaille's art has mapped her emotions on a daily emotion wheel. The project borrows from data art and procedural art because it involves continually collecting information.

During the Inclusion Mission, her emotions ranged from overwhelmed joy to energy-sapped fatigue.

It wasn't long before the onboard experience began shaping her art. She renamed the emotion wheel a "feelings rosette." In oceanography, a rosette sampler is an instrument that measures salinity, temperature, and other characteristics of ocean water.

Others on board began filling out feelings rosettes, too. Side by side, the rosettes revealed the emotional landscape of the voyage and the personalities of the people on it.

"The results also show how open or truthful a person can be in examining how they are feeling," Robitaille said.

Annie Tamalavage: Rekindling Passion

For paleoclimatologist Tamalavage, the Inclusion Mission signaled a return to sea voyages driven by curiosity, not just analytical research.

Modern natural science has its roots in early scientific voyages by Europeans seeking knowledge and wealth on distant shores. Charles Darwin penned detailed accounts of his observations as a naturalist on board HMS *Beagle* from 1831 to 1836. Just decades later, mariners on HMS *Challenger* laid the foundation of oceanography by sailing the world from 1873 to 1876, taking measurements of temperature, chemistry, and currents.

"Although we know early exploration has many conflicts related to colonialism and conquest, I have spent time trying to relate myself to these men from a scientific perspective," said Tamalavage, whose research project for the Inclusion Mission studied carbon transported through the mouth of the Romaine River over time as human industries morphed along its shores.

Deep philosophical pondering about our planet and a desire to explore were goals that connected the Inclusion Mission with historical journeys, said Tamalavage. The connection was made more potent by bringing together a diverse group.

"There was like a lot of emotion relative to the cruise, like everyone was kind of crying at various times," Tamalavage said. "When I could get on board and see and feel respected as a woman...I was just so hopeful and reminded [of] why I love this work in the first place."

Inclusion Mission 2.0?

Last summer, RQM also supported an LGBTQIA2S+ and woman-led scientific sailing expedition studying plastics in the St. Lawrence.

As with most research projects, said organizer Maxence St-Onge, funding is the main factor that will decide whether RQM will be able to reiterate and deepen the spirit of the Inclusion Mission in the years to come. "We really hope so."

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Reaching New Levels in Groundwater Monitoring

Climate change is contributing to severe droughts in the southwestern United States and elsewhere, increasing the afflicted areas' dependence on groundwater. In California, for instance, groundwater contributes up to 60% of the state's total water supply in dry years.

Small vibrations of Earth's surface "contain a wealth of information about the subsurface—if we can use them."

The aquifers beneath Los Angeles were one of three sets monitored using a new interferometry technique. Credit: Ron Reiring/Flickr, CC BY 2.0 (bit.ly/ccby2-0)

Monitoring subterranean aquifers is crucial to using their water efficiently—and ensuring that the supply doesn't run dry.

But monitoring groundwater isn't easy. Traditionally, an aquifer's water levels are measured using wells: Hydrologists drill into the ground and measure the pore pressure at depth, a measurement from which they infer the amount of water trapped in sediments. But drilling is expensive, and the measurements produce at best a scattered, incomplete image of an aquifer. Alternatively, satellite data can be used to trace deformations of Earth's surface, which swells up when the ground is waterlogged and subsides as water drains out, but surface data can't provide insight into what's underground.

Waves, Fast and Slow

Now, a new method may sidestep these problems by exploiting another source of information: seismic data. In a study published in *Nature Communications,* researchers made use of the fact that a seismic wave's velocity is related to the mechanical properties of the medium through which it travels (bit.ly/groundwater-fluctuations). If the traversed sediments are dry, waves propagate rapidly. If the sediments are saturated with water, wave speed is reduced. By analyzing differences in seismic wave velocities (a technique called interferometry), scientists can back calculate how much water is stored underground.

Because the method uses seismic waves, do scientists need to wait for big earthquakes to map the inner workings of aquifers? No. For her research, coauthor Shujuan Mao used records of so-called seismic ambient noise. "The Earth's surface is always vibrating due to ocean waves or human activity," explained Mao, a postdoctoral researcher in geophysics at Stanford University. "Those vibrations are very small, so we don't notice them, but they are recorded continuously by seismic stations and contain a wealth of information about Earth's subsurface—if we can use them."

In their paper, Mao and her coauthors did just that. "What's unique about our paper is that we not only measure the temporal changes [of relative seismic velocity] but also image those changes in space," she said. This imaging enabled them to construct a high-resolution map of groundwater distribution across 3D space and time.

Pumping Strategies Affect Groundwater Storage

The researchers used their method to examine aquifers in the Los Angeles (LA Central) and neighboring Santa Ana and San Gabriel basins, using data from about 50 seismic stations operated by the Southern California Earthquake Data Center. They found that groundwater storage fluctuates seasonally, with reserves more depleted in hot, dry summer months. Zooming out to longer timescales, the researchers noted an overall decreasing trend from 2000 to 2020, demonstrating that groundwater reserves were depleted more rapidly than they could recover.

This result wasn't unexpected, given the severe drought that gripped California from 2011 to 2017. But Mao and her group observed another trend that surprised them: While the San Gabriel and LA Central basins store less groundwater today than 20 years ago, the Santa Ana basin showed a slight increase in aquifer storage since 2000. Because there is no natural barrier between the LA Central and Santa Ana basins, researchers concluded that the difference is probably geopolitical: In Santa Ana, sustainable water management strategies ensure that pumping is adjusted to the amount of rainfall in a given year. In dry years, less water is pumped out, reducing the strain on aquifers. In contrast, LA Central and San Gabriel tend to use more water than is naturally replenished, leading to long-term depletion.

Although the dwindling status of groundwater reserves is worrying, Mao noted that her research has a silver lining: "In a way, the differences between counties are encouraging because they show that well-managed pumping strategies have a big impact." She is optimistic about the method's potential for informing those strategies. "It's not that we shouldn't use groundwater, it's just that we need a data-informed framework to decide when and how much to pump," she said.

"Well-managed groundwater pumping strategies have a big impact."

A Promising Tool for Probing the Subsurface

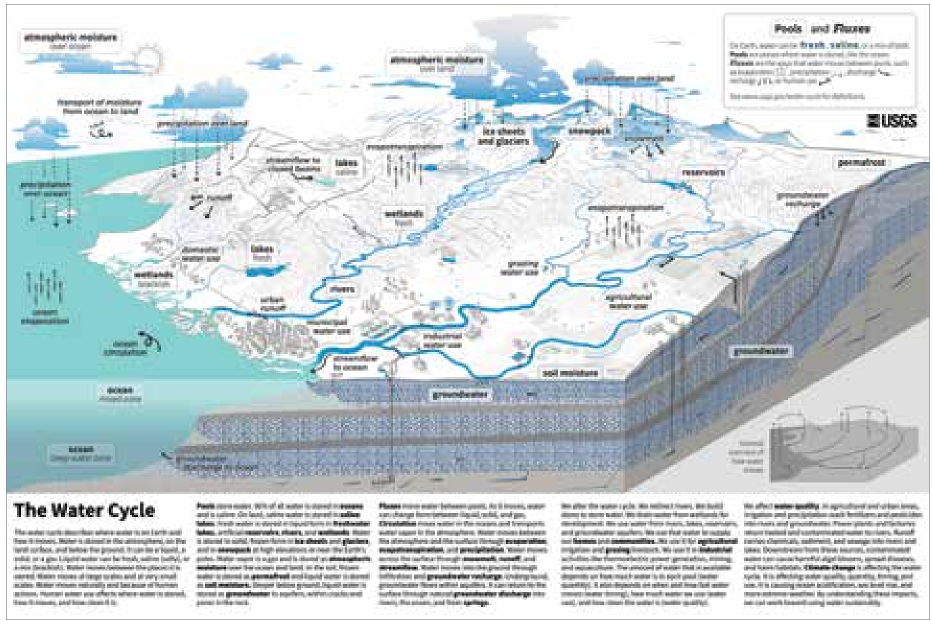
Ryan Smith, an assistant professor of civil and environmental engineering at Colorado State University who was not involved with the study, also considers seismic interferometry to be a promising technique. "The paper highlights an exciting new method and shows that it can be used to track groundwater levels in some regions with surprisingly good accuracy," he said, while noting that "since it's a new area of research, more investigation needs to be done on how passive seismic interferometry relates to changes in groundwater within different systems."

Smith concluded that with further development, "passive seismic interferometry has great potential to complement existing approaches for monitoring groundwater."

In her research, Mao continues to refine seismic interferometry as a tool for groundwater monitoring but is also excited to apply it to other problems. "This technique can be applied to many systems, like geothermal fluid operations, freezing and thawing processes in permafrost, and fracking," she explained. "With this profound data set—temporally continuous and in 3D—there are a lot of problems in the shallow subsurface that we can explore."

By **Caroline Hasler** (@carbonbasedcary), Science Writer

Not Your Childhood Water Cycle



Hayley Carson-Dosch/USGS VizLab

It's a sight most remember from childhood: a drawing showing the path of water from oceans to clouds to rivers. Long, lavish words like evapotranspiration and precipitation likely come to mind.

The U.S. Geological Survey (USGS) water cycle diagram is still used by hundreds of thousands of students in the United States and around the world. It's also the basis for many, many spin-off diagrams.

In mid-October 2022, the agency released a new diagram for the first time in more than 20 years, this time with humans as showrunners.

Although people have long siphoned water from groundwater and diverted rivers into farm fields and industrial plants, the new diagram is the first time humans have been included in what was presented until now as a "natural" cycle.

The change reflects the latest 20 years of research uncovering humanity's central role in the cycle and how to communicate it visually. "We need to change how we think about these things to be able to live and use water sustainably for our future," said Cee Nell, a data visualization specialist at the USGS VizLab, which designed the diagram.

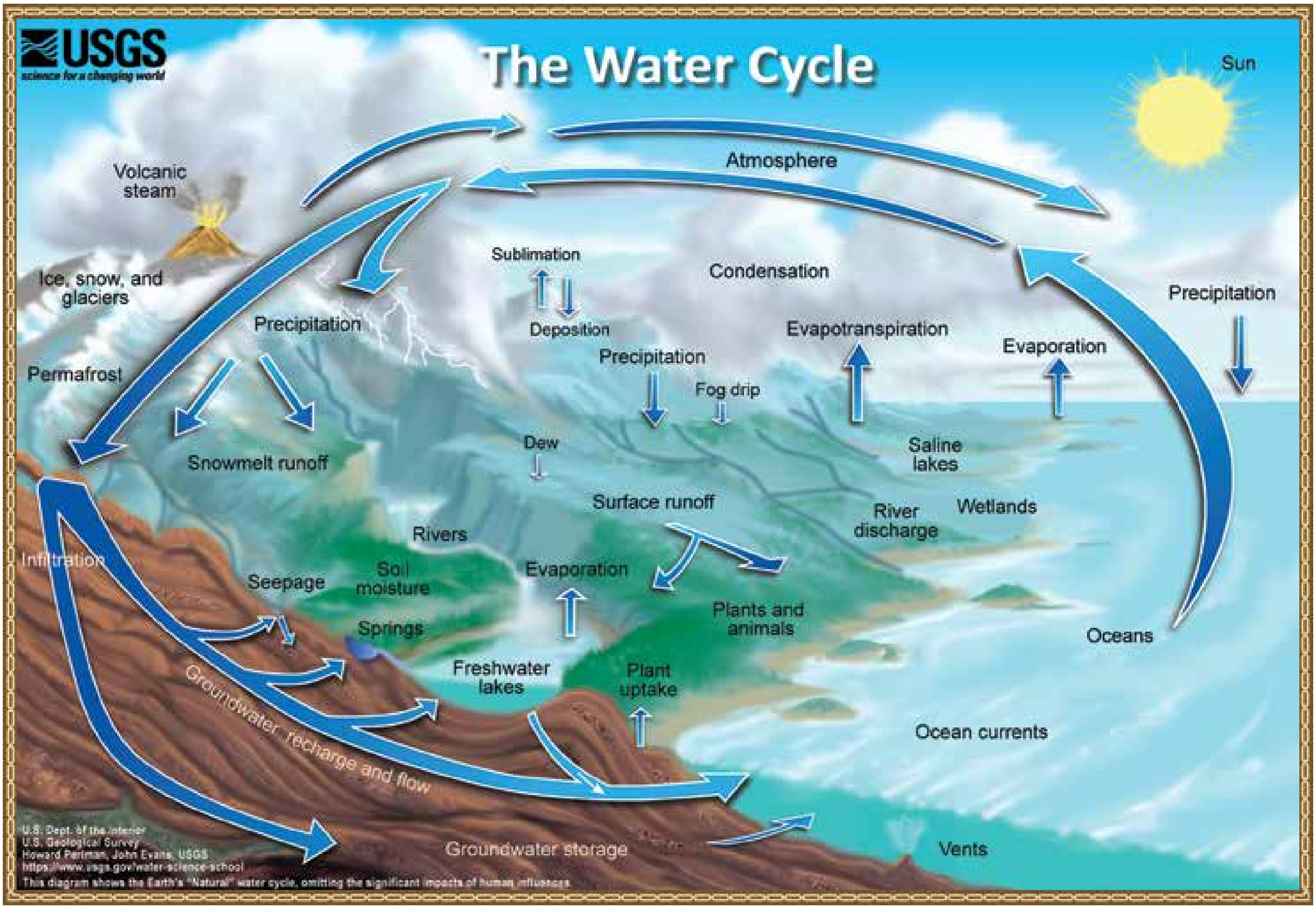
In addition to natural processes like ocean evaporation, precipitation over land, and runoff, the new diagram features grazing, urban runoff, domestic and industrial water use, and other human activities. Each label in the chart comes from data tracking the significant paths and pools of water worldwide.

"I think overall, this is a great improvement and an important step toward a more comprehensive depiction of the global water cycle,"

The new diagram is the first time humans have been included in what was previously presented as a "natural" cycle.

said ecohydrologist and biogeochemist Stefan Krause of the University of Birmingham, who was not involved in creating the diagram. In 2019, Krause contributed to a *Nature Geoscience* paper that called into question the lack of human activity or infrastructure in water cycle diagrams (bit.ly/water-cycle-humans). Of 464 diagrams analyzed, only 15% included human interaction with water.

"One misconception that could stem from diagram design is that the water cycle is just one big cycle," said Nell. The older USGS diagram showed a giant loop with arrows for water movement, for example. "We wanted to



The older water cycle diagram, used by the USGS since 2000, did not include human interference. Credit: Howard Perlman and John Evans/USGS

communicate that the water cycle is actually composed of many, many smaller cycles that are continuously going in different directions." Arrows in the new diagram are given a visual prominence similar to labels of pools where water is stored.

"There are a lot of hidden Easter eggs in there for somebody who really wants to spend time looking."

One of the most significant ways people use water in the United States is in thermoelectric power plants, where stream water is used as a coolant, said Nell. The water then travels back into the stream, sometimes affecting water quality. A thermoelectric plant was included in the diagram, as well as other features that aren't labeled. "There are a lot of hidden Easter eggs in there for somebody who really wants to spend time looking," said Nell.

Krause said he wishes there were nods to other aspects of human activity, such as altering rivers by straightening channels or using green water, as well as more explanation of some illustrations.

Accessibility drove the diagram's design, too. Using only one color, blue, alongside a gray scale for labels and landscapes creates a high contrast for visually impaired people, said Nell. The illustration's target age group is eighth grade, and it will eventually be translated into 60 languages. For now, it is available in English and Spanish.

"We want people to see the water; everything else is secondary. The details are nice,

"We want people to see the water; everything else is secondary. The details are nice, but those are going to be less visually prominent. The water is the main message."

but those are going to be less visually prominent," said Nell. "The water is the main message."

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Indian Cities Invest in Low-Cost Air Quality Sensors

In 2019, the government of India established the National Clean Air Programme for nonattainment cities (cities that did not meet the National Ambient Air Quality Standards). The program aimed to develop clean air action plans to reduce particulate matter ($PM_{2.5}$) pollution by 20%–30% by 2024. So far, this effort has been largely ineffective.

The program's inefficiency is partly due to a critical shortage of government air quality monitoring stations. Experts estimated that India needs 1,600–4,000 monitors. However, there are just 883 monitoring stations for assessing long-term air quality trends and 261 Continuous Ambient Air Quality Monitoring Stations, also known as Reference Grade Monitors (RGMs), that report the daily air quality index across the country. The discrepancy has resulted in gaps in data and underinformed mitigation approaches.

In 2021, the Commission for Air Quality Management, an agency that manages air quality in Delhi and the surrounding areas, recommended the use of low-cost sensors (LCSs) to address this discrepancy, but approval is pending because of misgivings about the accuracy and reliability of these sensors.

To test the precision and accuracy of low-cost $PM_{2.5}$ sensors, scientists from the Indian Institute of Technology (IIT) Kanpur installed 40 sensors next to government RGMs in Mumbai. The Maharashtra Pollution Control Board conducted this pilot project from November 2020 to July 2021. The results were published in *IEEE Sensors Journal*.

S. N. Tripathi, a study coauthor and professor of civil engineering at IIT Kanpur, said, "Our study shows that $PM_{2.5}$ LCSs have high precision and can achieve an accuracy of 80%–90% compared to the RGMs" (bit.ly/PM2-5-LCSs). Low-cost sensors are more maneuverable than RGMs, he noted, which allows them to have a higher temporal resolution and provide more specific geographic data.

However, the LCSs "need to be calibrated against RGMs before use," said Pratima Singh, an air pollution scientist at the Center for Study of Science, Technology and Policy (CSTEP), Bengaluru. "There has to be a standard framework on using these devices."

CSTEP assessed the performance of various $PM_{2.5}$ LCSs by comparing them with RGMs. They found that LCSs match the government sensors qualitatively but not quantitatively.

Working with Local Clean Air Guides

Tripathi said that cities are more inclined to use LCSs after his team's cautiously encouraging results. Studies are currently underway to use LCSs (in addition to RGMs) to assess air quality in Chennai, Jaipur, Guwahati, and other urban areas. "We have interesting observations that we would not get from the limited number of government monitors," he added.

For example, Smart Cities Mission, a federal initiative to promote sustainable development in cities, is using LCSs to quantify pollution at local levels. In 2021, Smart Cities Mission partnered with John Snow India, a health care consultant, to identify air pollution hot spots in Indore, a city of about 2 million in the state of Madhya Pradesh.

As part of the initiative, 20 community social workers were engaged as "clean air guides" and trained to use and interpret LCS data. Damodar Bachani, deputy project director at John Snow India, said, "The idea of using social workers was to educate people, particularly the urban poor, who don't know much about air pollution, so that they can take action to reduce it."

Data from sensors installed at 19 sites in Indore showed that sources of pollution varied from place to place. The main source of pollution was vehicles in commercial areas, manufacturing waste in industrial areas, and the burning of biofuels in residential areas.

The efficiency of low-cost air quality sensors is being tested throughout urban areas in India, including Mumbai. Credit: Ikshit Patel, Unsplash

"This community-based approach shows that you just can't take common decisions for the entire city, as sources vary, and therefore strategies to reduce pollution will also vary."

"This community-based approach shows that you just can't take common decisions for the entire city, as sources vary, and therefore strategies to reduce pollution will also vary," said Bachani.

For example, in places where the pollution levels were high because of traffic congestion, the city initiated a campaign called "Red Light On, Engine Off," which urged people to switch off their vehicles while waiting at traffic lights. The campaign witnessed a 20-point reduction in emissions.

Education efforts by clean air guides also influenced behavior in the community. People shifted to wet sweeping from dry sweeping, walking short distances rather than using transport, and planting more trees. Clean air guides also reported reductions in the burning of waste and the use of biofuels in slums and eateries.

Tripathi said the next steps are to test LCSs in rural areas to better understand rural air quality and the relationship between sources of pollution in rural and urban areas. Most rural areas lack government-run monitoring stations.

Low-cost air quality sensors were installed at 19 sites in the city of Indore and recorded varied sources of air pollution. Credit: Neeraj Mishra, John Snow India

Identifying Local Hot Spots

Pilot studies conducted with LCSs in rural parts of the Indo-Gangetic plain already have shown that $PM_{2.5}$ levels are quite comparable in different settlements across the region, irrespective of the settlement type—village, town, city.

Saumya Singh, a postdoctoral researcher at the University of California, Berkeley and lead author of the new study, said, "Low-cost sensors are helping us understand the urban-rural gradient. These results suggest that we need additional observations in rural settings about source dynamics and concentrations of $PM_{2.5}$."

Pratima Singh agreed that LCSs have their advantages, and CSTEP has installed a network of them in Bengaluru, Punjab, and Delhi to study different aspects of air pollution.

"Low-cost sensors have a high temporal resolution that helps identify hot spots at local levels, which RGMs cannot because of their incapability to be moved around," she said.

By **Deepa Padmanaban** (@deepa_padma), Science Writer

Long-Gone Moon Could Explain Birth of Saturn's Rings

A caterpillar emerges from its chrysalis as a butterfly, ready to dazzle the world with its beautiful wings. And according to a recent study in *Science*, a chrysalis at Saturn underwent its own transformation (bit.ly/Chrysalis-moon). Today the pulverized remains of a small moon—named Chrysalis by the study's authors—are dazzling the rest of the solar system as the planet's beautiful rings. The study argues that that scenario would explain not only the birth of the rings but Saturn's tilted axis as well.

"It's always nice to find solutions that can elegantly explain multiple different observations," said Tracy Becker, a planetary scientist at the Southwest Research Institute in San Antonio who studies Saturn's rings but was not involved in the new research. "It could explain Saturn's obliquity and the age and formation of the rings."

The project began with Jack Wisdom, a professor of planetary science at the Massachusetts Institute of Technology, and his colleague studying Saturn's obliquity, or the planet's tilt on its axis. Saturn and the other giant planets should have developed with a tilt of near zero, yet Saturn tips at an angle of 26.7°.

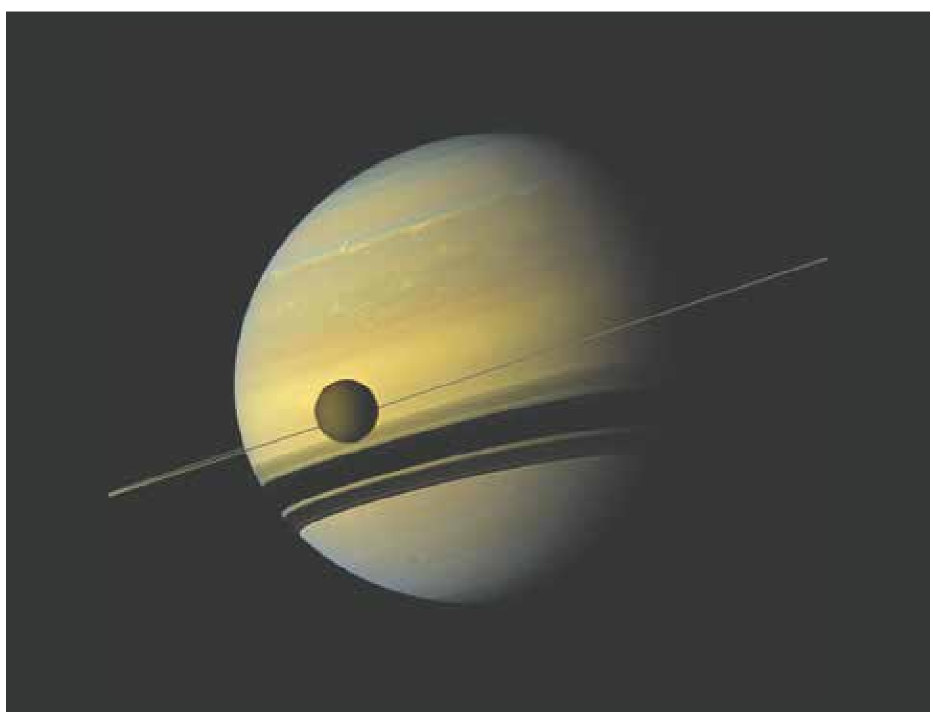
"Saturn is a massive planet, so it takes a massive force to tilt it like that," said Burkhard Militzer, a professor of Earth and planetary science at the University of California, Berkeley and a coauthor of the study. "Jack Wisdom said that even though it's far, far away, Neptune could do the job."

A resonance between a wobble in Neptune's orbit and a wobble in Saturn's rotation on its axis could have applied enough torque to change the axial tilt. Wisdom and others suggested that Saturn's largest moon, Titan, could also have played a part in that process.

A Possible Moon Comes to the Rescue

Dynamical simulations show that Saturn and Neptune are not in resonance today. However, "it's very close—about 1% away," said Wisdom. "We argued that because it's so close, it couldn't have been by chance."

"We were always so close" to an explanation, said Militzer, who studies the interiors



Titan passes in front of Saturn in this view from the Cassini spacecraft, with the edge-on rings forming a thin stripe and thick series of shadows. Titan could have played a crucial role in the rings' formation. Credit: NASA/JPL-Caltech/Space Science Institute of Saturn and other outer solar system giants. "It went on for weeks, and it was a big misery. What could get us to the critical value? Then the concept of this moon appeared. At that moment, what had been a problem became a real opportunity."

"You could add an extra satellite, and that would allow the obliquity to rise due to the resonance with Neptune as Titan migrated outward," said Wisdom.

Observations from NASA's Cassini spacecraft, which orbited Saturn from 2004 to 2017, showed that Titan is moving away from Saturn at a rate of about 11 centimeters per year. As Titan migrated outward, it altered Saturn's axial precession—a wobble that causes the axis to trace a big circle on the sky. Changes in the precession rate brought Saturn and Neptune into resonance. "About a billion years ago, Saturn entered the resonance with Neptune just by the migration of Titan," Wisdom said.

Simulations showed that the hypothetical moon, Chrysalis, probably orbited between Titan and Iapetus, Saturn's third-largest moon (though it's only about a quarter the diameter of Titan). Chrysalis was likely a little less massive than Iapetus, according to the study, and probably consisted mainly of water ice.

As Titan receded from Saturn, it created a 3:1 orbital resonance with Chrysalis, Wisdom said, which increased Saturn's tilt to as much as 36°.

The Titan-Chrysalis resonance made the moon system chaotic. Chrysalis's orbit was pumped to a higher and higher eccentricity, drastically altering the smaller satellite's distance from Saturn and creating closer and closer encounters with Titan and Iapetus. About 100 million years ago, its eccentricity doomed Chrysalis to being kicked out of the Saturnian system, causing it to crash into Titan or another moon or bringing it so close to Saturn that it would be ripped apart.

Chrysalis's orbit was pumped to a higher and higher eccentricity, drastically altering the smaller satellite's distance from Saturn and creating closer and closer encounters with Titan and Iapetus.

Wisdom's simulations didn't necessarily favor any of those scenarios. But one other factor argued for destruction by Saturn: the planet's rings.

As Chrysalis Disintegrates, So Does the Resonance

Scientists have long debated the origin and age of Saturn's rings. Today there's a consensus that they formed from the icy debris of one or more pulverized bodies—small moons or passing comets. There's less consensus on the age of the rings, however. Some have argued that the rings formed not long after Saturn itself did. Cassini observations, along with other work, suggest that the rings are much younger—perhaps 100 million or so years, matching the time frame for the disintegration of Chrysalis.

"This study predicts the breakup of a moon at around the time a lot of evidence is showing the rings might have been formed and gives a mechanism for how it happened," said Becker.

According to Wisdom, Chrysalis disintegrated when it passed by Saturn at roughly the same distance away as the planet's diameter. At that range, the side of Chrysalis closer to Saturn faced a stronger gravitational pull than the other side. The difference created powerful tides (just as the Moon creates ocean tides on Earth) that ripped the moon to shreds. Much of its debris fell into Saturn, and the rest spread out over the following hundred thousand years or so to form the rings.

With Chrysalis gone, Saturn's resonance with Neptune was broken. "Titan is continuing to recede, but as it recedes, the system gets farther from resonance, so [Saturn's] obliquity is no longer increasing," Wisdom said. And Saturn retains its magnificent rings, which might have emerged from a long-gone chrysalis.

By **Damond Benningfield**, Science Writer

Neighborhood Strategies Inform Boston's First Urban Forest Plan

Mattapan, a neighborhood in southwestern Boston, is heating up. Although some areas of the residential neighborhood benefit from the cooling effects of nearby green spaces, others are vulnerable to increasing heat stress, largely because of dark roofs, unshaded parking lots and pavements, and wide streets with limited numbers of trees.

Mattapan is one of five Boston neighborhoods identified as being at particular risk for heat stress. (The others are Chinatown, Dorchester, East Boston, and Roxbury.) The five neighborhoods, all environmental justice communities, are at the focus of Boston's heat resilience strategies, which include increasing the amount of light-colored surfaces and shade.

A big reason for the risk is the simple fact that there are fewer trees in these neighborhoods. For example, less than 25% of the land in East Boston (excluding Boston Logan International Airport) has adequate tree coverage.

Boston has recognized the importance of healthy tree coverage in addressing heat resilience and other climate change mitigation strategies. Credit: Mark Olsen/Unsplash

The plan's "neighborhood strategies" approach considers the unique ways in which each neighborhood has the ability to address particular issues and identifies the people within that neighborhood who are able to do something about them.

Boston has recognized the importance of healthy tree coverage in addressing heat resilience and other climate change mitigation strategies. In fact, the city developed its first urban forest plan—a pathway to maintaining existing trees, planting new ones, and otherwise helping the city deal with the effects of a changing climate (bit.ly/Boston-forest-plan).

"This plan essentially provides an analysis of the conditions in each neighborhood," said Neenah Estrella-Luna, the principal of StarLuna Consulting, a social equity researcher, and a consultant on the plan.

Neighborhood Strategies

The plan's "neighborhood strategies" approach considers the unique ways in which each neighborhood has the ability to address particular issues and identifies the people within that neighborhood who are able to do something about them. The approach employs the help of urban forest nonprofits like Dorchester-based Speak for the Trees, whose focus is on increasing the size and health of Boston's urban forest, particularly in undercanopied areas. Neighborhood strategies may also take inspiration from Lower Roxbury-based Friends of Melnea Cass Boulevard, which stopped a $25.6 million construction project that would have removed 124 mature trees, the *Boston Globe* reported.

This approach was driven entirely by the urban forest plan's equity council—a part of the larger community advisory board—and composed of individuals from historically excluded and currently marginalized communities across the city. The plan's consultant team organized a series of focus groups, which sent out a series of surveys to the equity council to establish overarching goals, the best strategic approach, protection regulations, expectations for the level of involvement from stakeholders, and more.

Responses were summarized and consolidated and went through three rounds of refinement, a process that allowed the equity cabinet to participate on its own schedule and its members to interact with one another. "That technique pushed for consensus building, as opposed to just whoever talks the most or the loudest, which often is how decisions get made," said Amy Whitesides, director of resilience and research at Stoss Landscape Urbanism and a consultant on the urban forest plan.

The neighborhood strategies approach also helped inform the plan's four goals: equity, community-driven processes, making sure trees are valued and prioritized, and proactive care and preservation of existing trees. The last tenet was especially important, Estrella-Luna explained. Before the drafting of the plan, "there just weren't sufficient resources devoted to particularly proactive protection of the existing canopy in historically excluded neighborhoods."

In spring 2022, the city halted renovation plans for Malcolm X Park, located in Dorchester, after outcry from residents. The plan threatened to remove 54 trees, many of which are more than a century old.

Hunter Jones, manager of the Climate and Health Project within NOAA's Climate Program Office, noted that Boston's neighborhood strategies approach is part of a larger trend in the United States. Jones identified air temperature, humidity, and even wind speed as factors contributing to urban heat and air quality issues across the country. "But increasingly," he said, "there's interest in looking at intracity differences."

By **Iris Crawford** (@IrisMCrawford), Science Writer

Seafloor Reveals a Period of Rapid Retreat for Thwaites Glacier

Antarctica's Thwaites Glacier suffered a period of fast retreat, doubling its current rate of shrinking, during the past several hundred years. This is the conclusion reached by an international group of researchers who acquired high-resolution imagery off the front of Thwaites. The group used state-of-the-art autonomous submersibles, which revealed unusual marks left on the seafloor by the retreating ice.

"It was like putting on your glasses for the first time and being able to see."

As large as Florida and several kilometers thick, Thwaites is one of the main concerns of scientists studying the Antarctic ice sheet. The melting of this mass of ice is responsible for 4% of present-day sea level rise worldwide. And warming waters and a seabed that deepens toward the ice sheet's interior have primed the glacier for a rapid collapse that could raise sea levels by more than half a meter in the next century.

Scientists don't know enough about the glacier's recent history to confidently forecast its future behavior, however. That's why a large British-American research initiative, the International Thwaites Glacier Collaboration (ITGC), was launched in 2017 to reveal the glacier's past and predict its future.

Telltale Ridges

In 2019, an expedition on board the *Nathaniel B. Palmer* icebreaker approached the front of the glacier and released a remotely operated submersible that mapped an area of 13 square kilometers of the seabed with specialized sonar and other instruments. As soon as the researchers recovered the submersible and looked at the images, they realized they had made an extraordinary finding. "None of us could explain what we were seeing," said Alastair Graham, an associate professor of geological oceanography at the University of South Florida and lead author of the new study. "It was like putting on your glasses for the first time and being able to see."

The images showed hundreds of parallel ridges covering an underwater plateau at depths ranging from 630 to 670 meters. The researchers think this plateau was a pinning point at a former grounding line, a region where the land-based glacier ends and the floating ice shelf begins. The ridges, ranging from 10 to 70 centimeters tall, were likely created by the glacier's front as it bobbed up and down with the tides. When the tide fell, the glacier pressed the sediments to produce one rib. The distance between ribs reveals how much the glacier receded during the daily tidal cycle—typically between 6 and 7 meters every day, but reaching up to 10 meters in some cases.

"In general, [the ridges are in] quite deep water, so they are below the reach of the main tidal currents and wave action," said Robert Larter, a marine geophysicist with the British Antarctic Survey who was the lead scientist on board the *Nathaniel B. Palmer* during the expedition. "And in many areas of the polar continental shelf there are very low rates of sediment accumulation, so [the ridges] don't get buried, either."

By looking at the ribs, the researchers realized they had a daily record of Thwaites's retreat over a period of 5.5 months. During that time, the glacier moved at a rate of 2.1 kilometers per year, twice the current rate as measured by satellite imagery.

Coming up with the mechanism that produced the ribs wasn't straightforward, though. The marks were so regularly spaced that they looked "made by humans," Graham said. "It took a long time for us to settle on an idea for what they might be and why they are forming." His analysis showed that the amplitude and height of the ridges follow a pattern that matches the region's natural tidal cycles, reaching a maximum in amplitude and height every 14 days. The findings were reported in *Nature Geoscience* (bit.ly/Thwaites-retreat).

The researchers don't know when exactly the ridges formed, but on the basis of Thwaites's current rate of retreat, they think the ridges aren't older than 200 years. Most likely, they formed around the 1940s, when neighboring Pine Island Glacier started retreating. A direct sample of the seafloor

The underwater robot Ran operated at the ice front of Thwaites Glacier from R/V Nathaniel B. Palmer *in 2019. Credit: Filip Stedt, University of Gothenburg* sediments could have allowed dating the ridges more precisely, but the scientists had to hastily leave the area when a mélange of icebergs and sea ice moved into the area in February 2019. This was the last time a vessel has gotten so close to the glacier, which has been encased by floating sea ice ever since.

Researchers expect that a new pulse of rapid retreat might occur if Thwaites migrates behind its current grounding line.

Similar Findings

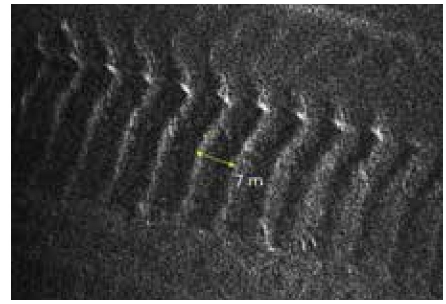
Unbeknownst to the scientists on board the *Nathaniel B. Palmer*, as they explored the seafloor in front of Thwaites, another group of researchers, led by Julian Dowdeswell with the University of Cambridge, was making a similar finding in Larsen Inlet on the other side of Antarctica. Using an identical submersible, this team found landforms that closely resembled those reported by Graham and his colleagues. However, these ridges were much older—about 10,000 years—and formed during the deglaciation of the Larsen shelf after the end of the last ice age. Dowdeswell and his team documented even faster retreat rates, reaching 40–50 meters per day, or more than 10 kilometers per year.

"It was really nice to see that a completely different science team had seen similar features in another area of Antarctica," said Christine Batchelor, a physical geographer at Newcastle University who coauthored the Larsen Inlet study, "especially as they had the same interpretation as to how the features are formed."

In both cases, the ridges were made of the material that accumulates underneath ice sheets—a mixture of gravel, sand, and mud that researchers call diamicton. Because it's compressed by the weight of the glacier as it settles into the seafloor, diamicton can remain stiff, Graham explained.

Possible New Pattern of Retreat

For Thwaites, the finding provides two important clues about the glacier's future. First, the glacier has the potential to retreat much more rapidly than its current rate. Second, the shape of the seafloor seems to play a key role in controlling the rate of retreat of the glacier, particularly when it retreats from



Ran revealed a series of parallel ridges in the seafloor in front of Thwaites. Credit: Ali Graham

flat-topped ridges, which is the present situation. For this reason, the researchers expect that a new pulse of rapid retreat might occur if Thwaites migrates behind its current grounding line.

The team hopes to obtain direct samples of the sediments forming the newfound ridges in front of Thwaites, whenever they can return to the area. In the meantime, they will turn to mathematical simulations to try to replicate how the process might occur.

By **Javier Barbuzano** (@javibarbuzano), Science Writer

Billion-Year Rewind Tracks Supercontinents and Mantle Structures

Earth's tectonic plates are always on the move and likely have been for much of our planet's history. Rewinding their paths, however, poses problems reaching past the most recent supercontinent, Pangaea, which broke apart around 200 million years ago.

To understand where continents once resided on the globe, scientists must choose a frame of reference. In a relative plate motion reference frame, one plate stays still—say, Africa—and everything else moves relative to that fixed piece of Earth. In contrast, absolute plate motion models let all the plates move within a reference system of the deeper Earth—holding hot spots or other deep mantle features constant, for instance. To complicate matters, both tectonic plates and the mantle move relative to Earth's spin axis.

By developing a new model based on letting tectonic plates and the mantle move together, a team of scientists explored how deep mantle structures might have responded to plate motions for the past billion years (bit.ly/billion-year-tectonics). The team, led by Dietmar Muller, a geophysicist at the University of Sydney, began with the time period when Pangaea's predecessor Rodinia existed.

Tectonics Rules! (Maybe)

Three tectonics-based "rules" govern Muller's model. First, he and his colleagues minimized how rapidly the lithosphere rotates relative to the mantle, a phenomenon called net lithospheric rotation. Muller explained that the high viscosity of the mantle limits the overlying lithosphere's wholesale movement.

Second, Muller's team restricted the mobility of subduction zones through the billion-year time span on the basis of how ocean trenches behave today. When an old, dense oceanic plate subducts, the hinge—where the plate bends—typically rolls back slowly, away from the overriding plate. Hinges rarely recede rapidly, nor do trenches often travel the other way toward the overriding plate, said Muller.

Third, because continents have a thick keel that sticks into the viscous mantle, Muller gave continents speed limits.

However, these rules may not apply to earlier episodes of Earth's history. Elvira Mulyukova, a geodynamicist at Northwestern University who was not involved in the new research, pointed out that the low-viscosity layer between the lithosphere and the rest of the mantle—the asthenosphere—is relatively weak. Therefore, the need to minimize net lithospheric rotation is an assumption, not a rule, she said.

Extrapolating today's slab rollback speeds to a billion years ago is another assumption, said Zheng-Xiang Li, a geologist at Curtin University who was not involved in the new research. Rollback may not have behaved as it does today, which means the speeds may have varied in the past.

> **"We do not know from observations how the mantle below our feet convects."**

Fast-Forward, Rewind

In Muller's preferred model, which starts 1 billion years ago, the ocean surrounding the supercontinent Rodinia contained scattered subduction zones. Until about 600 million years ago, the deep mantle structure reflected these distributed subduction zones. Ridgelike networks latticed around the core-mantle boundary, rising and falling like mountain chains made of dead tectonic plates.

Between about 600 million and 500 million years ago, a band of subduction zones helped distribute the continents around the circumference of the globe, with oceans on either side of the loop of landmasses. This resulted in distinct plume-spawning lower mantle structures beneath both oceans. However, the ever moving continents eventually ended their encirclement and dispersed. Subducting slabs sliced through one of the lower mantle structures, which disintegrated between 500 million and 400 million years ago. The other upwelling shifted, settling below the paleo-Pacific Ocean.

From 400 million to 200 million years ago, the Pacific-centered mantle structure took up its position, unbothered by subducting plates. However, no counterpart existed in the deep mantle on the opposite side of the globe, which instead housed a graveyard of subducted slabs thanks to the closure of ancient oceans as Pangaea coalesced, around 320 million years ago.

Eventually, Pangaea splintered, but the mantle structure underlying the Pacific persisted. After Pangaea's parts dispersed, the African mantle upwelling—possibly responsible for modern rifts and volcanoes—took shape.

Muller's model matches most other plate motion models for the past 200 million years of Earth history, in part because the recent rock record is much easier to reconstruct. In particular, today's ocean floor, striped with symmetric magnetic signatures that increase in age away from spreading centers, goes back 200 million years, letting Earth scientists more readily reverse the paths of continents, said Mulyukova.

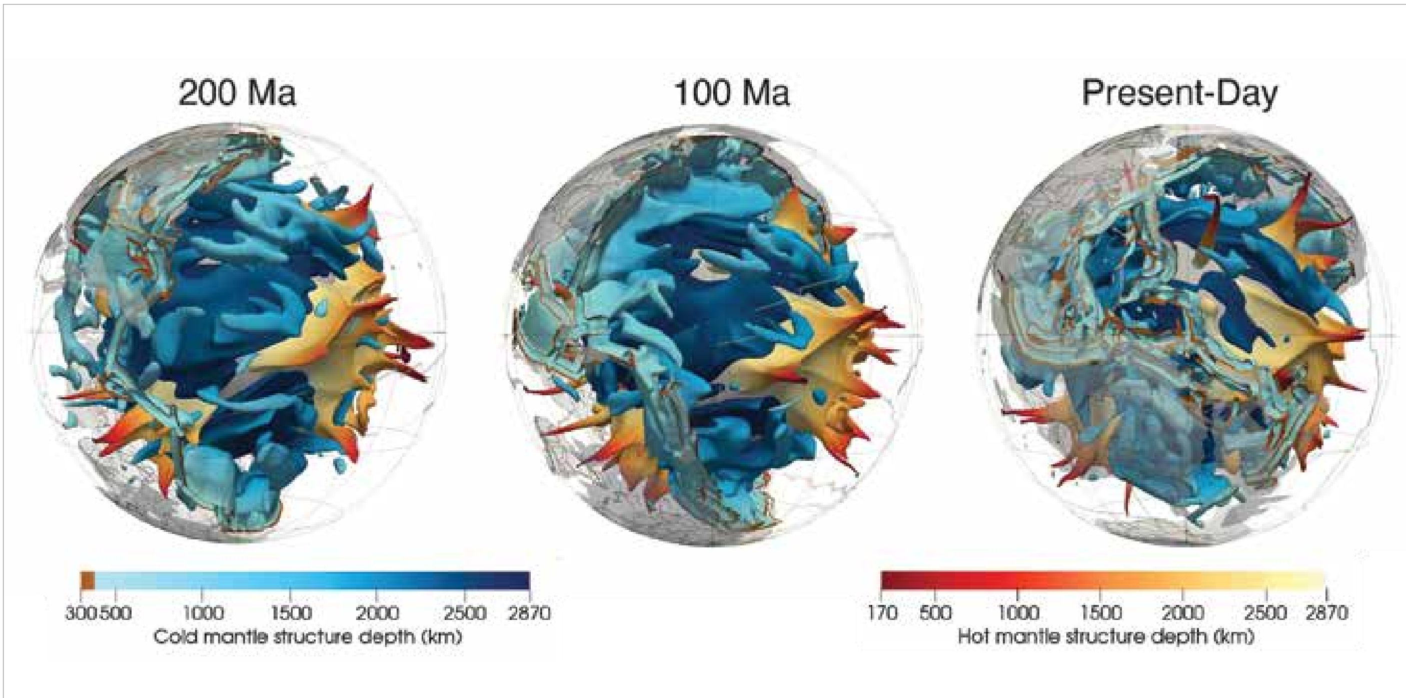
Beyond 200 million years ago, some plate motion models, when coupled to the mantle, yield unreasonable behavior like strange lateral mantle currents, explained Muller. "If we want to have a geodynamically reasonable model that obeys physics principles," he said, "we need to apply these rules."

Paleomagnetic Problems

Knowing whether the model's output is reasonable, said Muller, "is not that easy." As a check, he and his colleagues compared the model's past plate locations with known locations of volcanic eruptions, indicated by kimberlites and large igneous provinces, which originate from plumes deep within the mantle and have erupted throughout Earth's history. "We can simply compare where [deeply sourced volcanic regions] line up with the places where our model would predict a good likelihood of mantle plumes coming up," he explained.

Muller's model does not use paleomagnetic data as an external check in the same way as the deeply sourced volcanic information, in part because paleomagnetic data cannot constrain changes in longitude. This constraint means that if a tectonic plate traveled due east or west, that movement wouldn't be recorded in the paleomagnetic signal, said Muller.

Moreover, paleomagnetic data reflect motions of the plates relative both to the mantle (plate tectonics) and to the wholesale



This set of globes shows a 3D view of Muller and colleagues' geodynamic model results at 200 million years ago, 100 million years ago, and present day. These globes are centered on the Pacific Ocean at 150° east of the prime meridian. The gray region on the left of each globe shows the east coast of Asia to the north and Australia to the south. The orange and red colors show the hot mantle upwelling beneath the Pacific, with the blues showing cold mantle structures. Superimposed atop the mantle structures are the continents from 200 million years ago, when Pangaea began to break up, to present. The eastern Pacific coasts of Asia and Australia march eastward as subduction shrinks the Pacific. Credit: Ömer F. Bodur

rotation of the solid Earth—the crust and mantle together—relative to the spin axis (true polar wander), said Muller.

True polar wander, said Li, is a huge geodynamic process that can be modeled only indirectly in current models but, ultimately, must be incorporated to accurately use paleomagnetism data. When future geodynamic models can incorporate Earth's rotation and centrifugal force, then they could use paleomagnetic data as a check for the results, Li explained. "We have to really get over this hurdle to build Earth's spinning—the centrifugal force—into the geodynamic process," he said.

"Paleomagnetism Is the King"

"Geodynamicists have worked hard, from a modeling perspective, to understand how the Earth should behave," said Muller, by using physical constraints like mantle viscosity.

However, "within the current uncertainties of rheology [flow behavior] of the mantle…you can make models in which the mantle is almost stagnant or moving faster than plates," said Douwe van Hinsbergen, a geologist at Utrecht University. "We do not know from observations how the mantle below our feet convects."

As slabs subduct, their mineralogy and structure at the atomic level change, which can make a slab stiffer or weaker, said Mulyukova, "and therefore more or less capable to…shovel things around along the core-mantle boundary." Understanding these transitions from laboratory work and incorporating them into geodynamic models, she said, are important.

"I call it a second plate tectonic revolution."

Though temperature, and by extension density, is the main reason subducting plates sink, phase transitions, which occur as the physical properties of minerals morph into forms stable at higher pressures and temperatures, also contribute to the phenomenon. Phase transitions will change trench motions (Muller's second rule) by changing the pulling forces (like density and viscosity) that tug subducting slabs into the mantle, said Mingming Li, a geodynamicist at Arizona State University who was not involved in the new research.

Ultimately, using how the mantle might work and how plates should move to explain geological data "is the wrong way around," said van Hinsbergen. Instead, he argued that geological data—like paleomagnetism—should be used to explain mantle and plate behavior.

"My biased opinion is paleomagnetism is the king," said Mingming Li, who was otherwise very positive about the study. "There's no other handle to test the linkage between mantle structure and reconstructed absolute paleogeography."

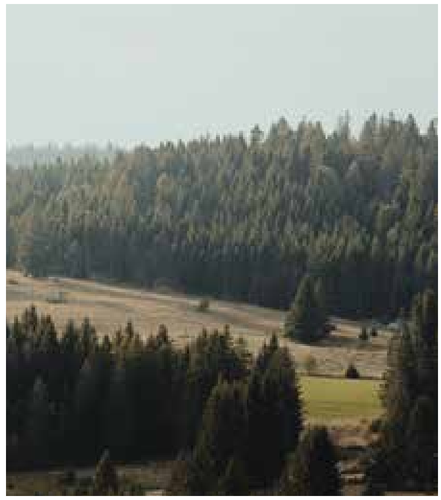
"We are bound by a lot of limitations," he continued, "but we are fortunate to live in a very exciting time. I call it a second plate tectonic revolution."

By **Alka Tripathy-Lang** (@DrAlkaTrip), Science Writer

Scientists Bring Forests into the Internet of Things

Forests have a complex relationship with climate change. On the one hand, they absorb atmospheric carbon, even proliferating amid changing climates. On the other hand, they can suffer under higher heat stress, degrading their carbon sink capacity and drought resilience. With some $10.5 million in funding from the German Research Foundation, scientists in Europe are planning to instrument forests with novel sensors to better understand how woodlands are affected by changing climate.

Mixing forest science with Internet of Things (IoT) technology, drones, and other devices, EcoSense will try to shed light on the effects of climate change on the interactions between plants, soil, and the atmosphere. These interactions vary according to species, location, and forest stand, which refers to collections of trees in a forest that are fairly uniform in age, size, distribution, and other factors. The EcoSense initiative will bring new technologies to forest monitoring following efforts such as Harvard University's wired forest.



EcoSense, a monitoring network in the Black Forest in southern Germany, will help scientists better understand the relationship between climate change and forest health. Credit: Michiel Annaert/Unsplash

"We do not understand when and why climate extremes like heat waves or droughts drive single trees or forest patches beyond their tipping points."

Specifically, the project will study abiotic and biotic processes of forest carbon and water exchange, as well as how the ecosystem responds to environmental stressors, enabling the prediction of process-based changes in ecosystem function and sustainability, according to a project outline (bit.ly/EcoSense-project). Real-time sensor network data will be transferred to a database for analysis and deep learning simulation models to generate short- and medium-term predictions.

"Climate change has a huge impact on forest ecosystems already. We see an increase in tree mortality worldwide," said Christiane Werner, a professor of ecosystem physiology at the Institute of Earth and Environmental Sciences at the University of Freiburg, pointing to the effects of the 2018 European drought. "Currently, we have well-established models to predict overall ecosystem functioning under nonstressed conditions, but we do not understand when and why climate extremes like heat waves or droughts drive single trees or forest patches beyond their tipping points."

Internet of Woody Things

The research team will instrument several hilly hectares of the Black Forest in southwestern Germany, covering stands of pure beech, pure spruce, and mixed trees. Climate-driven changes to the forest may have wider repercussions; the woodland is of economic and touristic importance to Germany, famed for its traditional farmhouses, cuckoo clocks, and eponymous ham and cake.

The EcoSense tool kit could include carbon dioxide (CO_2) sensors, camera-equipped drones, and other devices. The team will initially deploy commercially available devices and then, from 2024, replace them with newly developed microsensors, some of which will be energy autonomous, according to Ulrike Wallrabe, a professor in the University of Freiburg's Department of Microsystems Engineering.

"We want to measure fluxes of water, isotope-discriminated CO_2 and volatile organic compounds, and stress markers, mainly photosynthetic efficiency by chlorophyll fluorescence from soils up to atmosphere," said Wallrabe. "The sensor network will comprise new, compact, and, wherever possible, energy autonomous sensors that are to be developed in the project."

Daniel Kneeshaw, a forest and climate change researcher at the University of Quebec in Montreal who is not affiliated with EcoSense, said the project is examining interesting parameters that should be useful to a wide variety of researchers.

"As the researchers suggest, what happens at a cellular scale when scaled up can have profound impacts across regions," said Kneeshaw, adding that he wants to know how EcoSense data will be scaled up and down. "Better understanding of the mechanisms will help us be better prepared for future changes. Having such networks around the world and getting scientists from the different networks to talk [about them] will lead to even more robust results and interpretations."

The EcoSense project aims to begin publishing studies in 2023, but some groups affiliated with it have already started to release findings. For instance, one group including Werner published a paper on a wireless, autonomous chlorophyll fluorometer that measures photosynthesis efficiency in plants (bit.ly/chlorophyll-fluorometer). With a 10-kilometer range, the novel device can be attached anywhere on a tree and is low power and relatively inexpensive.

In addition to its initial 4-year funding, EcoSense has an option of two 4-year extensions to gain a long-term perspective. The researchers have high expectations of significant results.

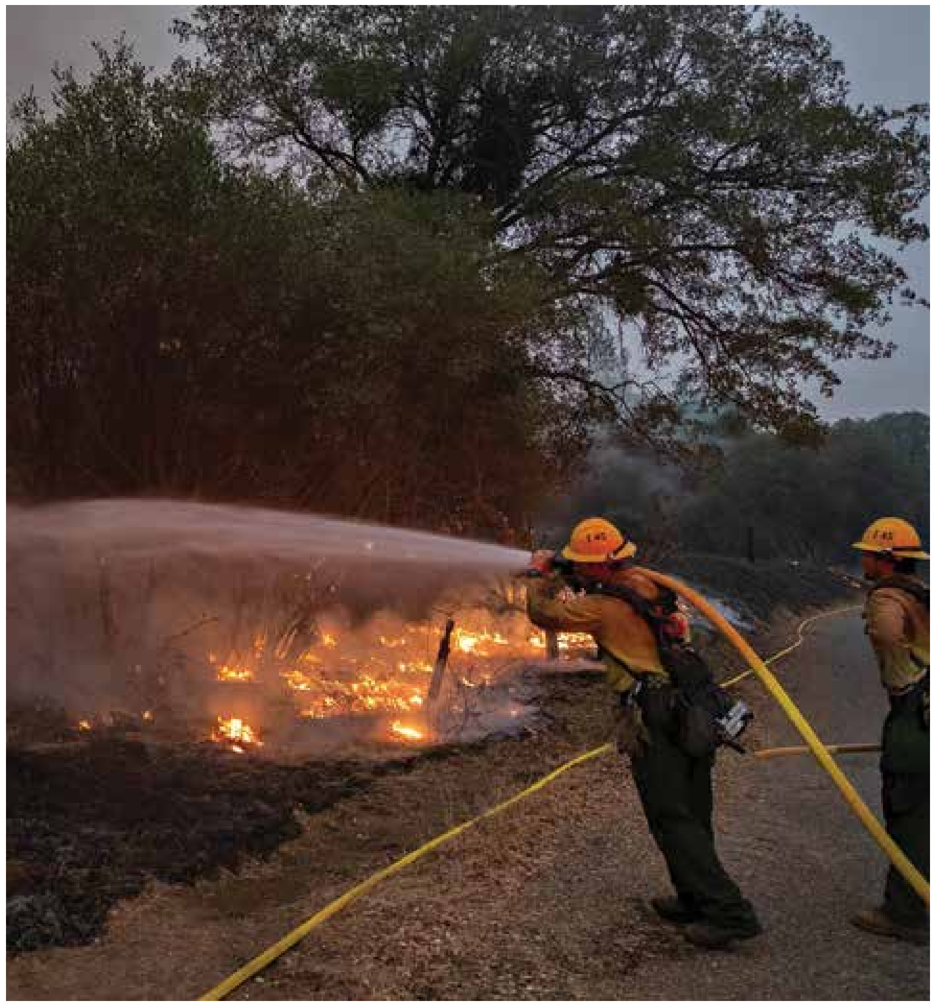
"Our special feature is the unique alignment of ecosystem research with microsystems technology. Distributed autonomous sensing principles will open a new door for ecosystem research," said Werner. "We will gain an unprecedented cross-scale coverage, both at the spatial level, from leaf to forest, as well as in a temporal dimension, from minutes to years, of processes and interactions driving carbon and water fluxes, including stress markers as volatile organic compounds and chlorophyll fluorescence."

By **Tim Hornyak** (@robotopia), Science Writer

Tackling Challenges of a Drier, Hotter, More Fire-Prone Future

Droughts, heat waves, and wildfires are among the costliest and most life-threatening disasters in the United States and worldwide. Wildfires in the western United States burned nearly 3.56 million hectares (8.8 million acres) in 2020, or about 75% more area than expected in an average year. With 37 people killed, tens of thousands more displaced, and millions having experienced impaired air quality, the total cost, including from health issues and indirect impacts such as disruptions of supply chains nationwide, is expected to be hundreds of billions of dollars [*Wang et al.*, 2021]. This record wildfire season, like many seasons in the past 20 years (Figure 1), occurred concurrently with a once-in-a-millennium drought and record heat across much of the southwestern United States (part of the Northern Hemisphere's warmest summer on record).

How do droughts, wildfires, and heat waves interact? How do they shape each other's likelihoods, magnitudes, and impacts? With millions of lives and billions of dollars at stake, answering such questions is vital in the United States and elsewhere around the world amid an uncertain climate future.



Firefighters work to contain the Creek Fire in Sierra National Forest in California on 10 September 2020. Credit: Pacific Southwest Forest Service, U.S. Department of Agriculture

How will vast burned landscapes shape atmospheric conditions favorable to droughts and extreme heat in coming years?

Concurrent droughts and heat waves can substantially increase fire risk and the scale of burned areas (although the degree of their impacts varies considerably with different fire regimes and histories). For example, tens of millions of trees died during the 2012–2016 California drought, creating a massive fuel load for wildfires [*Goulden and Bales*, 2019]. During the 2020 fire season in California, unusually strong back-to-back summer heat waves, punctuated by dry spells, made conditions ideal for the August Complex and Creek fires (Figure 2), which together burned more than 566,000 hectares (1.4 million acres), an area roughly the size of Delaware. Information about drought, heat waves, and the evaporative demand of the atmosphere is thus crucial for fire research and early-warning systems.

Less clear is how vast burned landscapes will shape atmospheric conditions favorable to droughts and extreme heat in coming years. With La Niña and warm North Pacific sea surface temperature anomalies lasting into early 2021, drought-favorable conditions are likely to persist over much of the western United States, independent of carryover effects from this past fire season. Will drought or extreme heat be established more quickly and intensely in newly burned regions or cause fire-favorable weather elsewhere? Global warming increases the co-occurrence of droughts and heat waves, along with concomitant wildfire risks. Scientists must characterize and quantify the potentially multiplicative impacts of these phenomena within and across warm seasons.

Challenges to Progress

We identify two principal challenges in advancing the science of and responses to drought–heat wave–wildfire events. First, feedbacks involved in shaping compound drought–heat wave–wildfire events are poorly understood, in part because there have been too few observed examples to identify robustly their shared origins and to model their co-occurrences statistically. Furthermore, many of the processes underpinning these events are also not represented well, if at all, in the physical models used to disentangle forcings and feedbacks. For example, models must better account for effects of fire-generated aerosols on subsequent rainfall; how reduced canopy densities of burned landscapes expose previously shaded winter snowpack to more solar radiation, leading to earlier melting in spring and reduced summer runoff [*Gleason et al.*, 2019]; and how fire-scarred vegetation and surface soils reduce evapotranspiration and water infiltration and increase runoff.

Addressing gaps between research disciplines requires collaboration among scientists with widely varying expertise.

Identifying the drivers of compound effects requires impact data, such as data describing drought impacts on the area burned by wildfires or the combined economic, environmental, and human health costs of drought, heat waves, and wildfire [*Zscheischler et al.*, 2020]. Until recently, however, wildfire was not widely considered to be an impact factor or feedback mechanism by the drought and heat wave research community.

The second challenge is that there are numerous barriers among disciplines and between researchers and decisionmakers in the study and risk management of drought–heat wave–wildfire events. Different disciplines view problems from their own angles. For example, drought researchers focus on variations in moisture supply (e.g., rainfall) as the primary cause of drought, whereas wildfire experts focus on the moisture demand of the atmosphere as indicated by vapor pressure deficits (Figure 2).

Addressing gaps between research disciplines requires collaboration among scientists with widely varying expertise, from climate physics, hydrology, and ecology to fire behavior and management science, air and water quality, and public health and infrastructure engineering. Adding the decisionmaking dimension, unfortunately, reinforces existing barriers. For example, scientists build their reputation on the thoroughness of their work, especially on understanding the limitations and uncertainty in their results. As such, they are reluctant to advocate for imperfect solutions. In contrast, risk managers are accustomed to working with imperfect (but timely) information to save lives and manage the impacts of hazards. Reconciling these differences requires cultural change in both fields.

Current Collaborations

In the past decade, coordinated efforts among scientists have significantly advanced drought research and early-warning capabilities. NOAA's Drought Task Force (DTF), for example, is composed of U.S. drought experts selected through a competitive proposal process run by NOAA's Modeling, Analysis, Predictions, and Projections Program in collaboration with the National Integrated Drought Information System (NIDIS). Over its 10-year history, DTF has led community research efforts to study drought causes, predictability, modeling, and monitoring that enhance early-warning capabilities in support of the NIDIS mission.

DTF and NIDIS have drawn top researchers from different disciplines to work together to address science questions central to drought early warning and management, especially those identified by stakeholders. For example, during the 2011 Texas, 2012 Great Plains, and 2012–2016 California droughts, DTF addressed the increasingly important role of heat in shaping these extreme events through timely reports about their dynamic causes, such as the role of sea surface temperature variability and anthropogenic forcing in producing them [*Seager et al.*, 2014; *Hoerling et al.*, 2015]. Separately, recent wildfire research has shown that warming, in addition to other factors like reduced precipitation and expansions of urban-wildland interfaces, is a leading cause of increasing wildfire in the western United States [*Williams et al.*, 2019] and worldwide.

The wildfire and climate research communities have already begun collaborating to create wildfire early-warning systems. For example, the U.S. Forest Service Wildland Fire Assessment System (WFAS), which is supported by the National Interagency Coordination Center (NICC), uses real-time drought and temperature information provided by NOAA to assess wildfire risk.

In 2015, the NIDIS Drought and Wildland Fire Nexus (NDAWN) initiative was established to improve drought information products and communication to drought and fire management communities. NDAWN partners with other drought and fire research and early-warning communities, including NICC and WFAS, to break down barriers to effective interdisciplinary collaboration.

Meanwhile, DTF supports projects that investigate the impacts of wildfire on clouds, precipitation, snowmelt, and streamflow over the western United States through both observational analysis and regional model simulations. And a growing body of research is aimed at developing a framework to characterize and quantify compound effects of droughts, heat waves, and wildfires [e.g.,

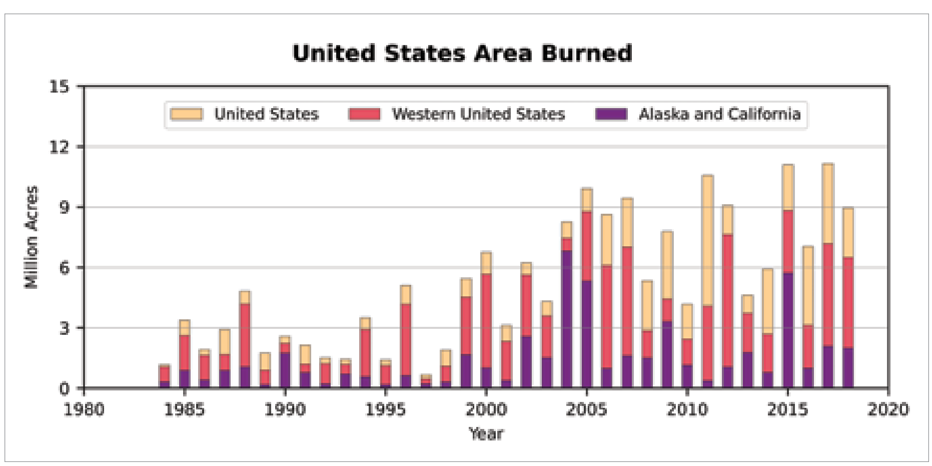


Fig. 1. Annual area burned from 1984 to 2018 in the United States in total, in the western United States, and in Alaska and California combined based on data from the federal Monitoring Trends in Burn Severity database.

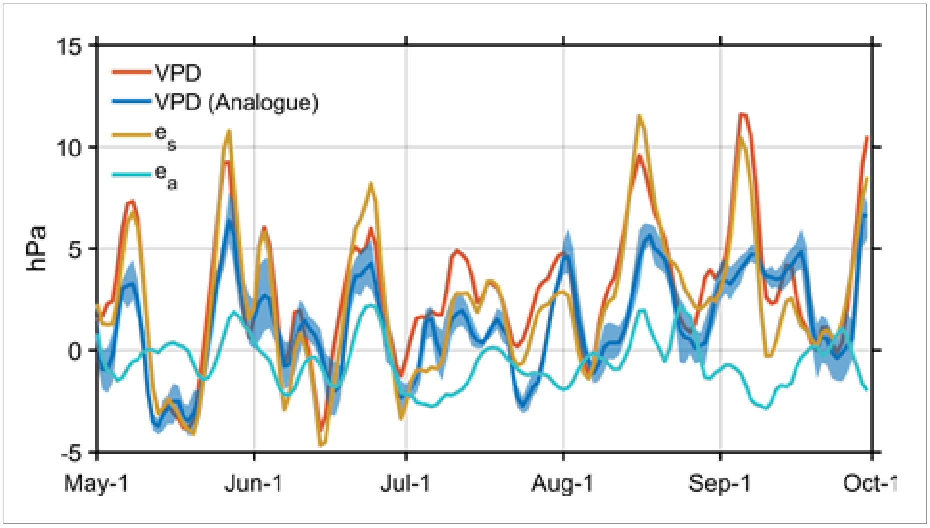


Fig. 2. Observed anomalous daily averaged vapor pressure deficit (VPD = $e_s - e_a$), vapor pressure (e_a), and saturation vapor pressure (e_s) in hectopascals (hPa) of surface air in Northern California between 1 May and 1 October 2020 obtained from gridMET data and smoothed as a 5-day running mean. "VPD (Analogue)" represents averaged VPD values and their 25%–75% uncertainty range (blue shading) for similar atmospheric circulation conditions in the same region from 1 May to 1 October of 1979–2019. The observed VPD for 2020 is mostly higher than we have ever seen in the recent past, mainly because of unprecedented warm surface temperatures during the 2020 fire season. Prior to the August Complex Fire in mid-August, dry anomalies (valleys in e_a) from 1 July to 1 August followed by a heat wave (spike in e_s) in mid-August created ideal climate conditions for wildfire fueled by dead trees. Prior to and during the Creek Fire in early September, another spike in VPD due to a heat wave in early September followed by a dry spell in early mid-September again created conditions for sustained wildfires. This plot illustrates how drought and heat waves work in concert to exacerbate wildfire risk in a changing climate

Zscheischler et al., 2020]. These, together with other existing efforts, will inform Earth system models with improved representations of ecosystem-fire-climate interactions, which, in turn, will ultimately enable researchers to dissect the underlying mechanisms of coupling among droughts, heat waves, and wildfires.

The wildfire and climate research communities have begun collaborating to create wildfire early-warning systems.

Opportunities for Improvement

How can we leverage current capabilities to make tangible progress? We need research support targeted toward early-career researchers who are working to increase the understanding of relationships among drought, heat, and wildfire and to develop key long-term collaborations with drought and wildfire managers. This support, along with revisions to the researcher evaluation metrics used by academic and research institutions to better account for and encourage high-risk research investments made by early-career scientists, is needed to sustain research programs that effectively address these societally impactful problems.

We should also raise awareness of existing scientific efforts, identify stakeholder needs, and foster and communicate shared and open science. For example, NIDIS and NDAWN can translate the latest research results into actionable information for stakeholders and provide feedback from stakeholders to researchers. Interdisciplinary science socialization of this kind, particularly when motivated by research imperatives identified by NIDIS and other stakeholders, can lead to insights that otherwise would be missed through narrower disciplinary research alone.

The combined impacts of droughts, heat waves, and wildfires are substantial and are outpacing mitigation and adaptation efforts. Consequently, there is broad shared interest among federal, regional, and state agencies and among private sector companies involved in weather, climate, wildfire, air, and water quality information to create an effective predictive capability. Coordinated efforts among research and application programs that leverage pooled resources are important not only for sustaining ongoing research that is addressing questions about drought, heat waves, and wildfire but also for seeding and expanding future interdisciplinary collaborations to ensure we have the science necessary to manage risks from compound extremes.

Acknowledgments

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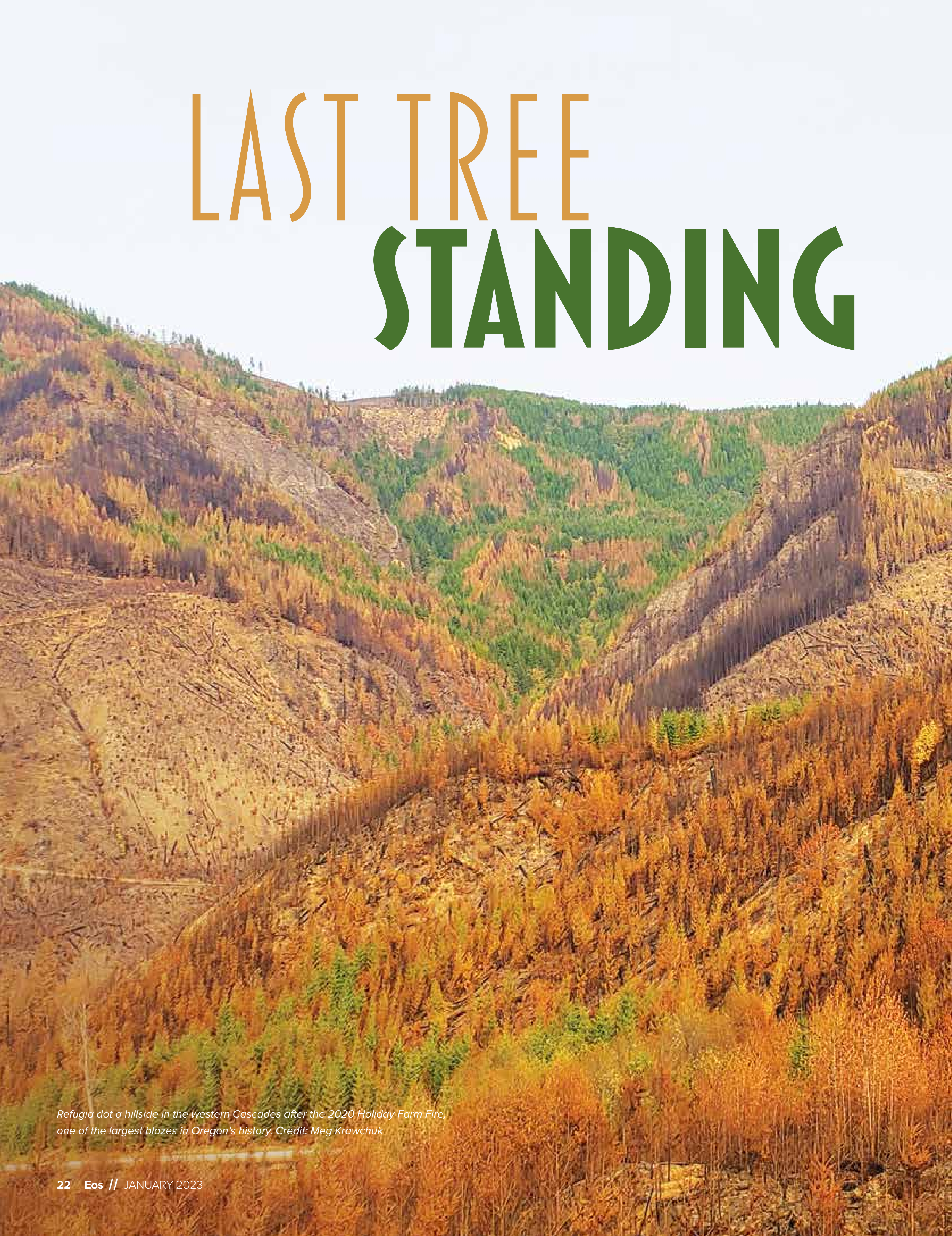
LAST TREE STANDING



Refugia dot a hillside in the western Cascades after the 2020 Holiday Farm Fire, one of the largest blazes in Oregon's history. Credit: Meg Krawchuk

Refugia repopulate forests after fires, but climate change is making these woodlands increasingly unpredictable.

BY ROBIN DONOVAN

Forest refugia are the oases of the woods, lush green patches that evade wildfires by quirks of topography, moisture, or the unpredictable wind and weather conditions during a fire. When fires subside, these patches of surviving trees and other vegetation repopulate nearby acreage as winds disperse seeds and spores across a charred landscape. Some refugia have persisted through fire after fire. Now, climate change threatens even these longtime survivors.

"The tricky thing is that as climate conditions continue to get hotter and drier and fire weather conditions tend to get a little more unpredictable and more extreme, the predictability of whether those persistent fire refugia will exist through future fire events is pretty uncertain," said Sebastian Busby, a fire ecologist with the U.S. Forest Service (USFS). Even the definition of refugia has expanded. It once meant an untouched oasis of persistent refugia but now can mean an area that is simply less burned than its surroundings or an ephemeral refugium that outlasts one fire but is burned by the next.

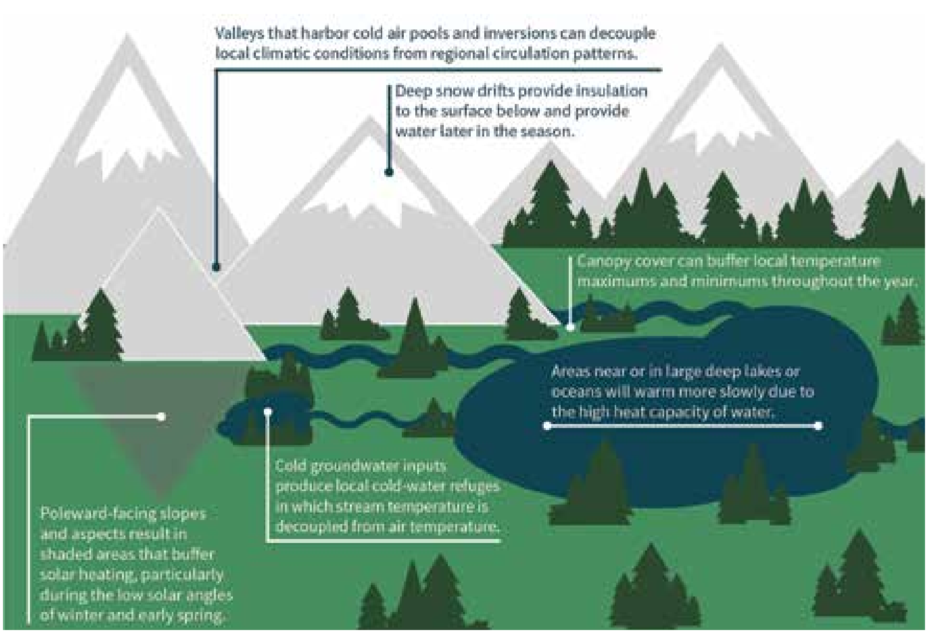
Refugia occur in many ecosystems, ranging from a few meters of rocks and plants to sizable stands of unburned trees, and aren't limited to forests. They can occur, for example, in climate-resistant patches of many ecosystems, such as deep lakes that are slow to warm, cold groundwater inputs, deep snowdrifts, and cold air pools in valleys. Any remaining trees, in the case of fire, can be considered refugia. And many, if not all, fire refugia are now also considered climate change refugia because of the link between our warming planet and hotter, more intense fires.

> **"KEEPING REFUGIA ON THE LANDSCAPE MAY ACTUALLY INHIBIT ADAPTATION BECAUSE YOU'RE ANCHORING DOWN A COMMUNITY THAT NEEDS TO SHIFT."**

"We have more tools to manage forest refugia than other refugia," said Toni Lyn Morelli, a research ecologist with the U.S. Geological Survey. Unlike other climate change–resistant spots, "forest stands can create their own microclimates that create refugia," Morelli added.

Scientists and forest managers alike are scrambling to define new best practices for both human-driven and hands-off management strategies as climate change shifts the role of these surviving pockets of trees. Fires today are harder than ever to predict. Warmer temperatures around the globe are now accompanied by longer, hotter fire seasons fueled by drought-stricken soil and vegetation in areas that were once too damp for flames to spread.

Although fire is an inherent and necessary part of many forest ecosystems, scientists don't yet agree on the best approach to managing fire and refugia. Some feel that the less intervention, the better, whereas others hope to guide forests to become more adaptable to the impacts of climate change, including fire. Although news cycles tend to focus on extinguishing large fires, bigger fires aren't necessarily bad; regions are characterized by unique patterns, or fire regimes, that vary in severity, frequency, and extent. Some forests, like the high-elevation, boreal forests of the Rocky Mountains, need high-severity fire to function. But high-severity fire in a region where this is not part of the typical fire regime is more troubling. Human impacts on fire's ignition and spread complicate the equation, adding new variables that influence when, where, and how fires start and grow.



Climate change refugia are "areas that remain relatively buffered from contemporary climate change over time and enable persistence of valued physical, ecological, and socio-cultural resources," according to the U.S. Forest Service. Credit: USFS

Piecing Together the Best Approach

Protecting existing trees and refugia at any cost threatens to throttle natural changeover to species that are more fire resistant, according to Oregon State University fire ecologist Meg Krawchuk. Despite specializing in refugia, she also knows that saving refugia at any cost is not the answer. "Keeping refugia on the landscape may actually inhibit adaptation because you're anchoring down a community that needs to shift," she said. "We think about fire as the ultimate catalyst that can potentially facilitate change by removing competition and allowing a playing field for adaptation to happen."

Managing forest refugia in the face of the climate crisis, Krawchuk said, means constructing a patchwork of approaches tailored to each forest. For example, old-growth forests might demand a resistance approach that prioritizes preserving as much of the original ecosystem as possible. In other regions, helping ecosystems rebound from fire could mean a healthy balance of allowing fire to progress naturally while also supporting recovery. Finally, recognizing that forests evolve, some regions might best be allowed to transition to new species with an eye to keeping various ecological roles intact (think one fire-resistant conifer species replacing another, less resistant species). Such a transition might mean letting even persistent refugia burn. Krawchuk said an approach using all three methods is best.

First, however, scientists must learn to predict how forests will respond to fire and where refugia will form. Only then can they effectively address the next controversy: whether, and how, to respond.

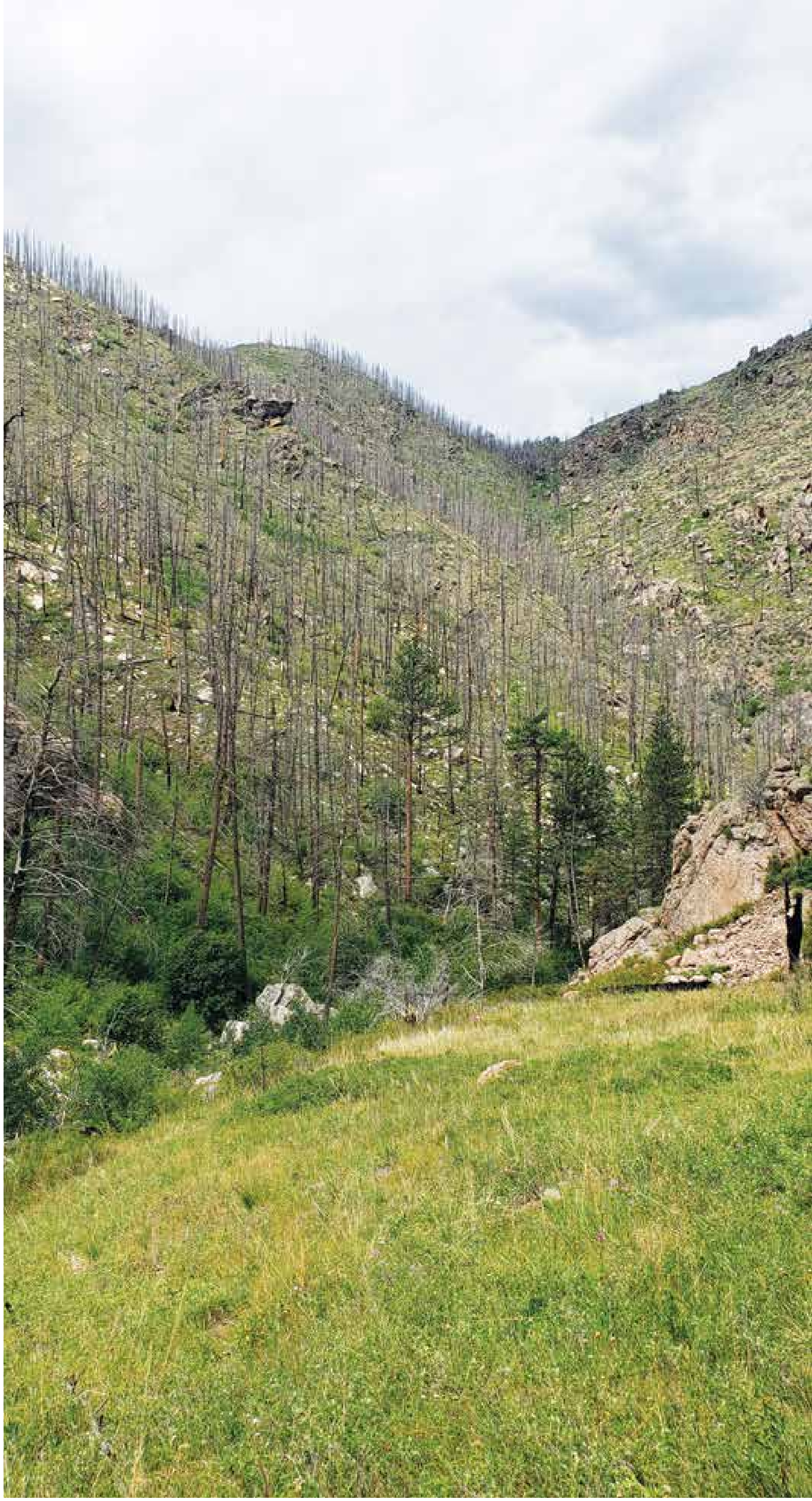
Far from Humans, Refugia Are More Resilient

Researchers in northeastern Siberia's larch forests found that wetness and terrain steepness predicted refugia, even during record-setting heat waves and ground and surface fires in 2020. After analyzing 2 decades of burns in these gently rolling landscapes, scientists found little change in refugia size and density. These regions are underlain by continuous permafrost, and refugia protect this frozen subsurface layer from thawing after fires, according to ecologist Anna Talucci, a postdoctoral researcher at Woodwell Climate Research Center in Falmouth, Mass.

Siberia's remote fires have created a patchily burned postfire landscape, a sign of healthy fire. Less burned patches, she said, which coincide with low-lying, wetter areas or trees growing on steep slopes, are more likely to yield refugia whose seedlings take advantage of wiped-out competition—smaller plants that might otherwise take root in the same soil as seedlings—to regrow after fires.

But Siberian larch forests don't burn the same way that North American boreal forests do. "The fires that we were looking at are not in mountainous regions," Talucci said, noting that the region's pattern of frequent, smaller surface fires is governed by conditions on the ground. "And so it's really those microsite characteristics that seem, in the context of this study, important for influencing fire refugia." Fires in northeastern Siberia tend to be ground or surface fires, which wipe out low-level plants and shrubs that would otherwise compete with larch seedlings. Ground fires, which can smolder in the earth for months, spread slowly but can be harder to extinguish than surface fires that consume dry and dead vegetation just above the ground.

In contrast, North American boreal regimes include crown fires that blaze destructively through an interlaced network of treetops, leaving behind few refugia. Some high-intensity fire is needed in these regions, and boreal forests can adapt to these fires over time, so not all larger fires are ecologically catastrophic. But crown fires coupled with shifting conditions due to climate change have led to extreme blazes in recent years.



In Colorado's Cache la Poudre River valley, the 2012 High Park Fire was ignited by lightning. Credit: Meg Krawchuk

Bushfires devastated The Spectacles Wetlands, part of a parkland just south of Perth, Australia, in 2019. Credit: Calistemon/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

North America and Australia's Unruly Blazes

Fire weather, a factor in all types of fire, is governed by a triad of factors: drought and dryness, temperature, and wind, which can quickly fuel an inferno when paired with an ignition source like lightning or a campfire left unattended. In North America and Australia, extreme conditions have contributed to historic burns in recent years.

In the 1990s, wildfires burned an average of 526,000 to 2.5 million hectares (1.3 million–6.1 million acres) in the United States each year. In the past decade, that average has topped 4 million hectares (10 million acres) several times. As of mid-September 2022, 2.7 million hectares (6.7 million acres) have burned in the United States. Fires that have become bigger and hotter, combined with population growth, have led to more and more people living in fire-prone regions. As fires began sooner each year and ended later, California's Department of Forestry and Fire Protection stopped measuring fire seasons in favor of fire years, and USFS followed suit.

The 2019–2020 Australian "Black Summer" megafires burned 14.3 million hectares (34 million acres), affecting approximately 80% of Australians and causing 34 deaths, along with the loss of more than 2,700 homes.

Extreme Fires, Unpredictable Refugia

"The more extreme the fire weather conditions, the less effective the topographic controls are in impeding fire completely but also in moderating the burn intensity," or how much vegetation is consumed by fire, said ecologist Brendan Mackey, who directs the climate change response program at Griffith University in Queensland, Australia. Instead, enormous, intense fires can be accompanied by similarly extreme weather patterns. Even normally protective features like pockets of moisture on a north facing slope on the U.S. West Coast can be overpowered by the outsized temperatures of recent fires. In other words, extreme fires become so hot that they can overcome these protections.

This extreme behavior means that it is harder to predict how fires will ignite and spread as well as where and when refugia will be left behind. Not only does this make it more difficult for scientists to agree on how to manage fires, even if they did agree, the unpredictable nature of contemporary burns makes any strategy other than simply leaving fires alone that much harder to implement.

When it comes to predicting fire behavior and resulting refugia, there's something of a "Goldilocks effect," according to Krawchuk, in which moderate fires—as well as refugia in areas with moderate topographic variation—tend to be more predictable, whereas very mild or very intense fires, increasingly, are not. In fact, hotter, more intense blazes can create their own weather, including wind, thunderstorms, massive clouds, and even tornadoes. In addition to dryness, temperature, and wind, "we've been joking that that's sort of the fourth axis of what we refer to as the fire behavior triangle: fire itself," Krawchuk said.

Meanwhile, efforts to understand and manage refugia are still in their infancy. "We are just beginning to conserve refugia," Morelli said. "I think there are a half dozen projects in the world on it." These range from studies of whitebark pine in Wyoming, to refugia in Canada's high-latitude boreal forests, to climate-sensitive Joshua trees in Southern California.

Seed dispersal and other phenomena that help repopulate forests are complex events that are still being mapped and studied. Even in areas with fire regimes not characterized by crown fires (like Siberia), it's become harder to predict whether and where forest regeneration might occur and thrive as permafrost ebbs. Burned parts of even healthy, patchy forests that vary in burn severity may be too far from refugia for seedlings to spread and thrive. Conifer reproduction, for example, relies on the timing of masting events in which trees produce a bumper crop of seeds. These seeds can travel only as far as the wind takes them, often just 100 meters (328 feet) or so from live trees. (One species of Siberian larch has a mean dispersal of just 15 meters, or about 49 feet.) When seedlings can't establish themselves quickly in burned areas after masting, hardier vegetation moves in to take advantage of newly exposed mineral soil. Late-arriving seedlings face fierce competition, which slows repopulation.

How Humans Can Help

A recent review of 49 studies of postfire forest regeneration in the United States found that only six of those studies directly analyzed climate metrics like moisture deficits or seasonal precipitation. Some studies did indirectly take such climate change outcomes into effect, but drawing direct links between refugia and, say, droughts could help scientists learn precisely when to intervene.

"I don't believe we can't find predictable refugia just because of climate change," Morelli said.

Scientists are still figuring out when and how to support forests after fires. Updating models for how far trees can disperse seeds and adding nuance to debates about thinning forests, prescribing controlled burns, and incorporating Indigenous practices could help as fire-prone regions set new records.

"We as scientists need to come up with and develop tools that are user friendly for [forest] managers in order to do these more complex calculations," Busby said.

Tough budget choices might be on the horizon, too. Although it's tempting to prioritize saving old-growth forests and vulnerable stands of trees, balancing these efforts with protecting refugia that encourage biodiversity and regrowth could become equally important.

"We're always going to focus on preventing fire in fire-prone regions," Morelli said. But "some places are going to have to burn, either because we can't stop it or because the only way we're going to get through this period is [to accept that] some burning is going to have to happen."

Even in forests where high-intensity fire is part of the typical pattern, too many larger fires without a healthy balance of smaller, brush-clearing blazes can wipe out refugia, according to Krawchuk. Forest managers in areas like New Mexico and Arizona that historically had patterns of small, brush-clearing fires are now paying the price for decades of fire suppression; these states may need to learn to rely on smaller, "pocket" forest refugia, Krawchuk said.

Longer, more severe fire seasons have also stretched the duties of forest managers who are responsible for various agencies' firefighting efforts, as well as managing forest conditions that predicate fires. That increasing burden makes it tough for ecologists' research to make its way to exhausted managers, who have less and less time to digest new best practices when fire seasons wind down.

IN THE CASCADES, ARID REGIONS REQUIRED HUMAN INTERVENTION TO REGROW, BUT WETTER AREAS FARED WORSE WHEN SCIENTISTS STEPPED IN.

"They're usually grieving the loss of their landscape or perhaps even worse, and then they're having to go back into project planning," Krawchuk said, noting that she does not work with managers directly.

Some forest managers say they are working with scientists to incorporate the latest research into their work. Monte Williams, a USFS forest supervisor at Colorado's Arapaho and Roosevelt national forests and Pawnee National Grassland (ARP), said his region is "luckier than most" because of its proximity to a local university and research station. "Researchers and scientists influence and often directly participate in the planning and execution of the work on the ARP," he said. Local practitioners, in turn, provide feedback to researchers.

Still, learning when and how to intervene in the face of less predictable fires is crucial. Cultural burning practices from Indigenous groups like the Karuk, Hoopa Valley, and Northern Sierra Miwok tribes in California and the Noongar people, among many others in Western Australia, are another option. They prescribe controlled, predictable "cool burns" that clear brush and promote biodiversity. These practices largely stopped when Indigenous Peoples were removed from their lands during colonization, but recently, new partnerships have reintegrated this Traditional Ecological Knowledge.

Given the uncontrollable nature of megafires, not everyone agrees that humans should intervene at all. "Minimizing human perturbation overall in a forest is becoming a necessary contingency given we can't really predict where refugia will be next time," Mackey said. He believes that many current interventions are outdated and hurt more than they help because, for example, controlled burns may predry regions that wind up burning anyway.

Researchers from Portland State University in Oregon were curious to see whether some human interventions are worse than no action at all. They analyzed forest refugia and regrowth after a fire. Sometimes, they found, replanting by humans helps forests regrow. But when humans step in unnecessarily, the outcome is worse than if they'd done nothing. Busby led the study, comparing the regrowth of wet, mesic forests with drier, desertlike regions in the Cascade Mountains. He and his team found that arid regions required human intervention to regrow, but wetter areas fared worse when scientists stepped in. Human-planted trees in wet areas filled in alongside natural regrowth, forming doubly dense tree stands—a kind of superfuel for future fires.

"There's really no need to replant those areas even though all of the prior trees were wiped out," Busby said of his study, which was specific to the Cascades, a wet, high-elevation forest. "There needs to be a little more evaluation done around when it is actually necessary to replant versus having this warm and fuzzy feeling of 'we're going to help the forest and go out there and replant' when it might actually not be necessary at all."

No forest is immune to climate change, even if some have avoided crude practices, like fire suppression, or controversial ones, such as salvage logging, Mackey said. And if we can't currently predict the next refugia, is simply minimizing human impacts our best bet? Krawchuk has focused her research on figuring this out. As she's zoomed in on climate change impacts, she's defined climate change slow lanes, including forest refugia, that seem to resist them.

"There's a geography that we need to understand more clearly of the variability in the speed of the change that climate change is painting across our landscapes," she said. And if parts of the landscape can take care of themselves, there are also refugia that are teetering toward losing their protective qualities. After generations of fire interventions, fire ecologists like Krawchuk can only race against climate change with new research, hoping the right management practices will encourage forests to burn, regrow, and evolve.

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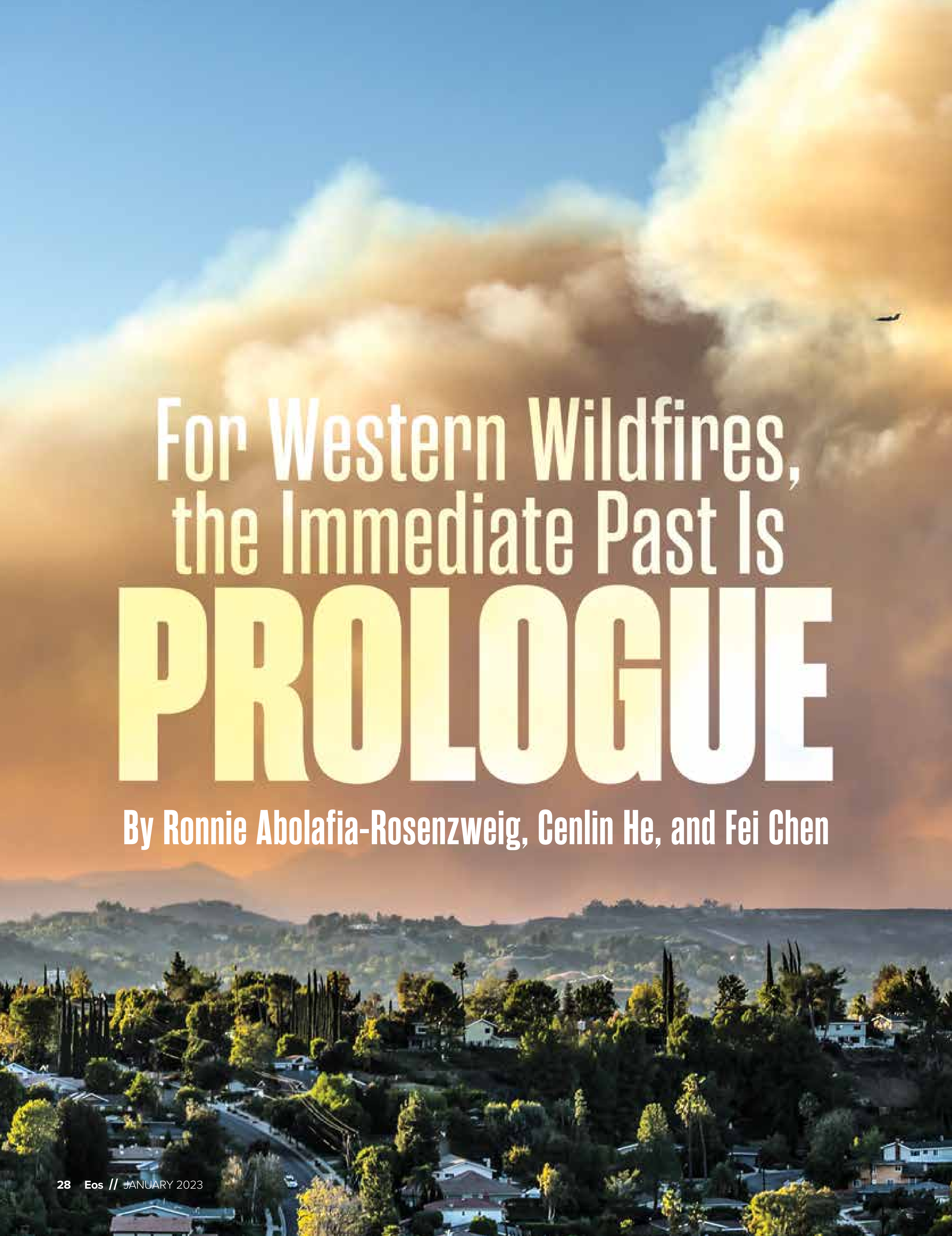

For Western Wildfires, the Immediate Past Is PROLOGUE

By Ronnie Abolafia-Rosenzweig, Cenlin He, and Fei Chen

A new machine learning approach trained on winter and spring climate conditions offers improved forecasts of summer fire activity across the western United States.

Smoke from the Woolsey Fire billows over the Southern California landscape near Malibu on 9 November 2018. Credit: Peter Buschmann/U.S. Forest Service, public domain

Since 1984, satellites have observed a growing trend in summer wildfire activity in the western United States, with the total burned area increasing by 104,000 acres (42,100 hectares) per year on average [*Abolafia-Rosenzweig et al.*, 2022]. From 1984 to 2000, wildfires across an area including all or parts of 11 states burned about 27.4 million acres in total, whereas from 2001 to 2018, this figure grew to about 55.9 million acres. In 2020 alone, the burned area jumped to roughly 8.7 million acres—equivalent to 32% of the cumulative area burned from 1984 to 2000—and the 2020 and 2021 fire seasons combined burned almost 15 million acres of the western United States, an area nearly as large as West Virginia.

This trend is largely attributable to longer and drier fire seasons caused by human-induced global warming [*Abatzoglou and Williams*, 2016; *Zhuang et al.*, 2021]—and it is likely to accelerate. Projections out to 2050 suggest that the climate of the U.S. West will be twice as conducive to forest fires compared with that of the 30-year period from 1991 to 2020 [*Abatzoglou et al.*, 2021].

In spring 2020, Jimy Dudhia, a scientist at the National Center for Atmospheric Research, asked us whether established relationships between climate and fire can be used to forecast fire activity accurately. This question ignited our curiosity, fueling research to find out whether weather in the winter and spring can reliably predict the severity of the fire season the following summer.

The Climate-Fire Connection

The western United States is in the midst of an unprecedented period of widespread megadrought and fire activity that exceeds the severity of any other period observed in available millennia-long paleorecords [*Williams et al.*, 2022; *Higuera et al.*, 2021]. We have seen and felt the impacts of wildfires firsthand from our drought-stricken hometown of Boulder, Colo., over the past 2 years. We have evacuated our homes to escape several wildfires, and we have witnessed neighborhoods burn to the ground amid the devastating Marshall Fire last winter.

On a national level, these fires cause thousands of smoke-related deaths, destroy thousands of homes, have increased COVID-19 mortality, and have led to persistent changes in ecosystems and water supplies. Suppressing these fires requires government expenditures that frequently exceed $1 billion annually. Thus, accurate forecasts of fire activity across a broad scale are becoming increasingly important for efficiently allocating resources required for wildland firefighting. Close relationships between climate and fire in the West, which are leveraged by our fire forecasting systems, may also motivate policy intended to reduce greenhouse gas emissions, which are heavily contributing to heating, drying, and increasingly severe wildfire seasons in the region [*Abatzoglou and Williams*, 2016; *Zhuang et al.*, 2021].

The tight coupling between climate and fire in the western United States has been enhanced by the legacy of fire suppression and a lack of prescribed burning associated with colonization starting around 1800, leading to historically dense forests. Fire prediction models based on climatic conditions can help validate whether land management strategies like tree thinning and prescribed burning can counter the effects of the heating and drying and weaken the climate-fire coupling. For instance, if climate-based predictions of fire activity become less skillful following large-scale forest management strategies, then the strategies used are likely useful for mitigation.

Fires cause thousands of smoke-related deaths, destroy thousands of homes, have increased COVID-19 mortality, and have led to persistent changes in ecosystems and water supplies.

Previous research established that most of the year-to-year variability and the overall trend in fire season severity over the past 4 decades in the western United States can be explained by climate fluctuations [*Riley et al.*, 2013; *Abatzoglou and Kolden*, 2013; *Williams et al.*, 2019; *Abolafia-Rosenzweig et al.*, 2022; *Westerling et al.*, 2006]. This correlation exists because the flammability of trees, grasses, and brush (i.e., the fuel for fires) and the rate of fire spread fundamentally depend on how dry the fuels and surrounding environment are. Fire spread involves a series of ignitions caused by heat from a fire raising neighboring fuels to their ignition temperature (Figure 1). Once enough heat has been transferred, the fuels combust. When fuels are moist, extra energy (latent heat) is required to evaporate the water and dry them before their temperature can reach the ignition point. This basic concept of thermodynamics has played a key role in regulating the year-to-year variability of broad-scale fire activity in the western United States, and it is expected to continue to do so as long as there is an abundance of fuel [*Abatzoglou et al.*, 2021].

Machine Learning Quantifies Fire Burning

We reframed Dudhia's question as our central hypothesis, positing that much of the variability and trend in summer burned area across the West is explained by prefire climate conditions alone. To test this hypothesis, we developed and evaluated statistical models that "learn" historical relationships between presummer climate and summer fire activity in the western United States [*Abolafia-Rosenzweig et al.*, 2022].

The machine learning methodology we used involved inputting combinations of presummer (i.e., winter and spring) climate conditions, or predictors—each averaged over varying presummer periods—into generalized additive models (GAMs). GAMs are linear models adapted to learn features in and model nonlinear data sets. The predictors considered included precipitation, temperature, evapotranspiration (the movement of water from soil and plants into the air), potential evapotranspiration (the atmospheric demand for water), vapor pressure deficit (the dryness of air), and drought severity and area.

From more than 100,000 potential models, each based on a unique combination of predictors, we selected the 100 best for use in an ensemble prediction system on the basis of how well each could fit satellite observations of burned area (as determined by minimizing a metric called the Akaike information criterion). We then evaluated the predictive ability of our multimodel ensemble by comparing the burned areas it predicted for past years held out of the model training data with observed burned areas during those years. Accuracy on held-out data—referred to as cross validation—is considered the gold standard for machine

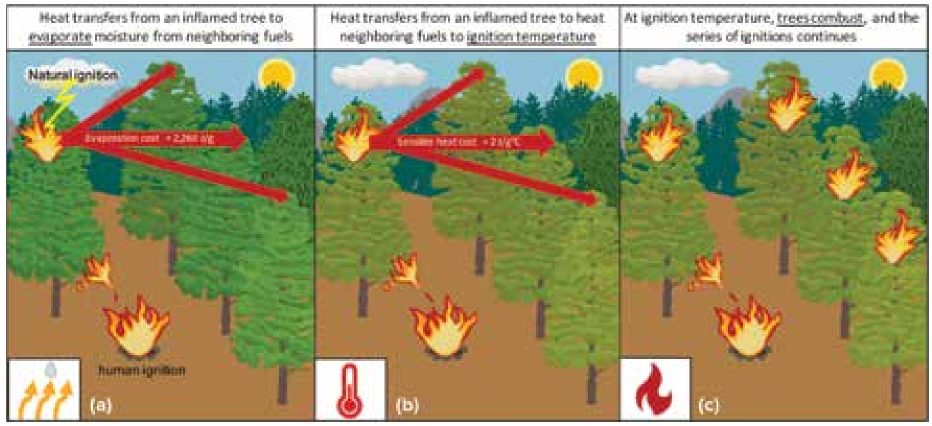

Fig. 1. Wildfires can spread after an ignition source (e.g., a campfire or lightning) sets fuel on fire. (a) In the case illustrated here, heat from the burning tree dries neighboring trees via evaporation, consuming a large amount of energy (latent heat of vaporization, 2,260 joules per gram). (b) After the neighboring trees are dry, additional heat coming from the ignited tree raises the neighboring trees' temperatures (via sensible heat flux) until they reach ignition temperature. The specific heat of timber (2 joules per gram per °C) determines the energy required to produce this temperature increase. (c) At ignition temperature, these trees begin to combust, and the series of heat transfers and ignitions continues.

learning evaluation. Namely, we performed both leave-one-year-out and retroactive forecasting cross validations.

In leave-one-year-out cross validations, models are trained with data from all years except the target predicted year, which is left out. Because this target year is not used to train the model, the prediction made for this year is called an out-of-bag prediction. This procedure is performed for every year in the study period to assess a full record of out-of-bag predictions. Retroactive forecasting mimics an operational forecasting system in which models are trained with records only from years prior to a target year to predict the target-year fire activity. In our case, we produced retroactive forecasts for the years 2002–2020, with the 2002 retroactive forecast, for example, using models trained on data from 1984 to 2001.

Both cross-validation methods depicted robust relationships and predictability between presummer climate and summer burned area across the western United States in our model ensemble ($r \geq 0.73$, where 1.0 represents perfect correlation), supporting our central hypothesis [*Abolafia-Rosenzweig et al.*, 2022].

The 2022 Summer Forecast

We recently applied the methodology described above to a new model ensemble tasked with forecasting the total western U.S. burned area for summer 2022 (June–September). This experimental forecasting effort examined the portion of the contiguous United States west of 104°W and contained within the four western regions defined by the National Integrated Drought Information System (NIDIS) drought early warning systems (DEWS): Pacific Northwest, California-Nevada, Missouri River Basin, and Intermountain West. Predictions were made with a 1-month lead time, considering prefire climate predictors from November 2021 through April 2022.

The model ensemble mean predicts nearly half of the interannual variability of summer burned area from 1984 to 2021 on the basis of pre–fire season climate ($r = 0.7$; Figure 2). And the predicted trend in burned area over this time suggests an increase of 62,000 acres per year, explaining 60% of the observed trend of 104,000 acres per year. Furthermore, the model ensemble predicts whether the burned area in a given year was above or below average with 82% accuracy. These models thus explain much of the year-to-year variability and trend in fire activity over the past 4 decades. To our knowledge, no other macroscale forecasting system for burned area has outperformed our new ensemble.

The portion of variability in observed burned area that is not explained by our approach is likely explained by a combination of factors that were not used to train our model. Such factors include fuel availability, local wind patterns, ignition sources, and the rapid onset of midsummer or late-summer drought. Part of the explanation for the model ensemble's underestimation of the trend in increasing burn area is that our pre–summer climate models do not directly account for the relatively substantial trend in summer warming—summer temperatures across the West have warmed by 0.033°C per year on average from 1984 to 2021—which is not represented by winter and spring temperature trends (<0.014°C per year).

For the 2022 fire season, our machine learning approach experimentally forecasted a burned area of 3.8 million acres, an area roughly the size of Connecticut.

Large underestimates of the total areas burned during the 2020 and 2021 fire seasons also partially contributed to the underestimated trend by our model ensemble. Our statistical models inadequately accounted for late-summer drought intensification across the western United States in 2020 that enabled unprecedented late-summer fire activity. This activity included the devastating August Complex Fire in California, which consumed more than 1 million acres. The failure to capture the extreme extent of burned area in 2021 is likely because of the rare severity of the drought that year, which is not reflected in the model training data.

In general, statistical models that forecast fire activity on the basis of historical relationships may exhibit diminishing accuracy in a rapidly changing climate system because future conditions could frequently fall outside the range of historic variability. Indeed, four out of five of our ensemble's least accurate predictions were for anomalously active fire seasons in just the past 10 years (2012, 2017, 2020, and 2021). Yet such models, which can continually be improved with additional training, are still highly valuable and useful, especially in the absence of other reliable means to forecast the intensity of coming fire seasons.

For the 2022 fire season, our machine learning approach experimentally forecasted a burned area of 3.8 million acres—an area roughly the size of Connecticut—although this figure could have ranged from 1.9 million to 5.3 million acres considering the uncertainty quantified from the range of predictions from the full model ensem-

Ash and smoke from the two largest fires in Colorado's recorded history fill the sky above Chautauqua Park in Boulder on 16 October 2020. The Cameron Peak Fire burned 208,913 acres, and the East Troublesome Fire burned 193,812 acres. Credit: Ronnie Abolafia-Rosenzweig

ble. This forecast corresponds to the eighth-largest total burned area over the western United States in the model's 1984–2022 record (Figure 2a), and it is 38% larger than the average summer (June–September) burned area from the simulated 1984–2021 record.

The severity of the predicted burned area for summer 2022 was attributable to below-average winter–spring precipitation and above-average winter–spring temperatures resulting in widespread spring drought conditions (Figure 2b). However, monsoonal summer rains reduced fire risk throughout much of the western United States, contributing to a below-average area burned during the historical peak fire months (June-September) of 1.74 million acres, making summer 2022 less active than most summers since the start of the satellite record in 1984. Prior to the arrival of the rains, spring drought had favored the most fire-active May since 1984, with 0.64 million acres burning, mostly in Arizona and New Mexico where conditions were driest (Figure 2b). We therefore plan to update our experimental forecasting methodology to include May as

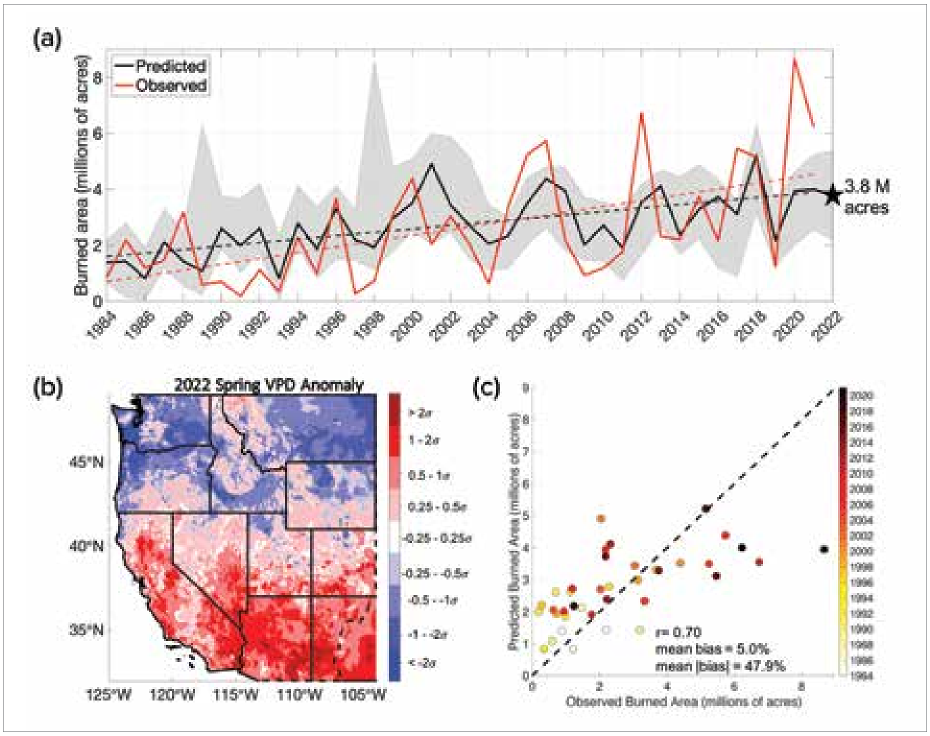

Fig. 2. (a) A time series of observed annual summer fire season burned areas shows the increasing trend since 1984, which has been punctuated by extreme seasons, such as in 2020. The experimentally predicted fire season burned area for 2022 was 3.8 million acres (black star), which is the eighth largest in the model's 39-year record (and ninth largest in the satellite record). All results shown here are from a leave-one-year-out cross validation with 1-month lead time predictions. Gray shading shows the 95% ensemble range. Black and red dashed lines show the linearized trends of modeled and observed burned area from 1984 to 2021. (b) Spring vapor pressure deficit (VPD) normalized anomalies (σ) relative to the 1984–2022 record are shown across the experimental domain considered in this work, which is bounded by the dashed line. Blue and red shades represent lower and higher VPDs, respectively, relative to the long-term average. (c) Dots (colored by year) represent model-predicted versus observed summer burned areas. The overall prediction accuracy is reported as correlation (r), mean bias, and mean absolute bias.

part of the fire season to account for fire seasons beginning earlier in a warmer and drier climate, and to use forecasts of summer hydroclimate (e.g., monsoonal rainfall) as predictors for machine learning models.

Using and Improving Fire Forecasting Systems

Forecasts of cumulative burn area and fire activity can inform resource allocation decisions in advance and on a national scale. Specifically, for example, forecasts of the extent of summer fire activity can inform the amount of money allocated to suppress fires during the peak fire season. These forecasts are also important in helping convey that broad-scale fire activity in the western United States has been and is expected to continue to be driven primarily by climate. Amid discussions of greenhouse gas emissions targets, climate, and corresponding legislation, policymakers can apply this understanding to craft sensible legislation aimed at reversing trends of worsening wildfires.

The abilities of statistical models to predict western U.S. wildfires accurately are challenged by rapidly changing climate, fire regimes, human behavior, and corresponding vegetation changes. To help mitigate model inaccuracies, scientists can account for fuel availability using satellite-observed vegetation indices and should consider using physically based weather models to further train fire prediction models with information about potential summer hydrometeorology (e.g., precipitation), local wind patterns, and natural ignition sources (i.e., lightning). Researchers should continue to investigate how climate-fire relationships are strengthened or weakened by human-induced ecosystem changes and by new climate and fire regimes in the Anthropocene [*Littell*, 2018]. With such ongoing research and model development efforts, we hope the region will be better equipped to foresee and respond to future wildfires and to reduce their devastating impacts on people and nature.

Acknowledgments

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A LIDAR'S-EYE VIEW OF HOW FORESTS ARE FARING

By Van R. Kane, Liz Van Wagtendonk, and Andrew Brenner

Building the perfect campfire requires the right mix of ingredients: plenty of kindling, a spark to ignite it, and large, dry logs to keep the fire burning strong. Unfortunately, fire suppression strategies adopted long ago—combined more recently with severe droughts and climate change—have created this same mixture writ large across many of the dry forests of the western United States, such as those in Yosemite National Park and elsewhere in the Sierra Nevada. Over the past several years, these conditions have led to disastrous, headline-grabbing fires that threaten human communities, ecosystems, and the very survival of our forests.

Despite their destructive power, fires are natural phenomena in many forests, where they are essential to the biomes' long-term health. Decades of field-based studies have built the field of fire ecology and have built the field of fire ecology and have informed nuanced views of fire as both a threat and a restorative process. However, the expense of such fieldwork has meant that relatively small portions of forests—and their relation to fire—have been studied in detail. Even extensive field studies involving hundreds of forest plots may cumulatively measure conditions over only dozens to hundreds of hectares, yet because of the limited data available, these samples are taken to represent

This artificially colored 2019 lidar image from Yosemite National Park shows built infrastructure and open spaces (white and gray) interspersed amid the forest. Credit: NV5 Geospatial

Success in Yosemite is driving the wider use of lidar surveys to support forest health and wildfire resilience, study wildlife habitats, and monitor water resources.

Lidar allows us, for the first time, to quantify forest structure directly, a feat previously possible only by painstaking field measurements.

highly varied conditions over millions of hectares.

Today, with help from remote sensing technologies, fire ecologists are more often examining continuous forest landscapes to understand their conditions before and after fires. In particular, they are using high-resolution laser imaging measurements gathered by lidar instruments aboard planes to map conditions from the treetops to the ground. Lidar allows us, for the first time, to quantify forest structure directly—that is, to determine tree heights, canopy densities, and the distribution of branches and leaves throughout the canopy—a feat previously possible only by painstaking field measurements. Lidar-based studies are beginning to enrich our understanding of wildfires historically, and they are providing forest managers with new tools to use in planning forest restorations and thus to improve forests' resilience to future fires.

A New Understanding of Fire in Forests

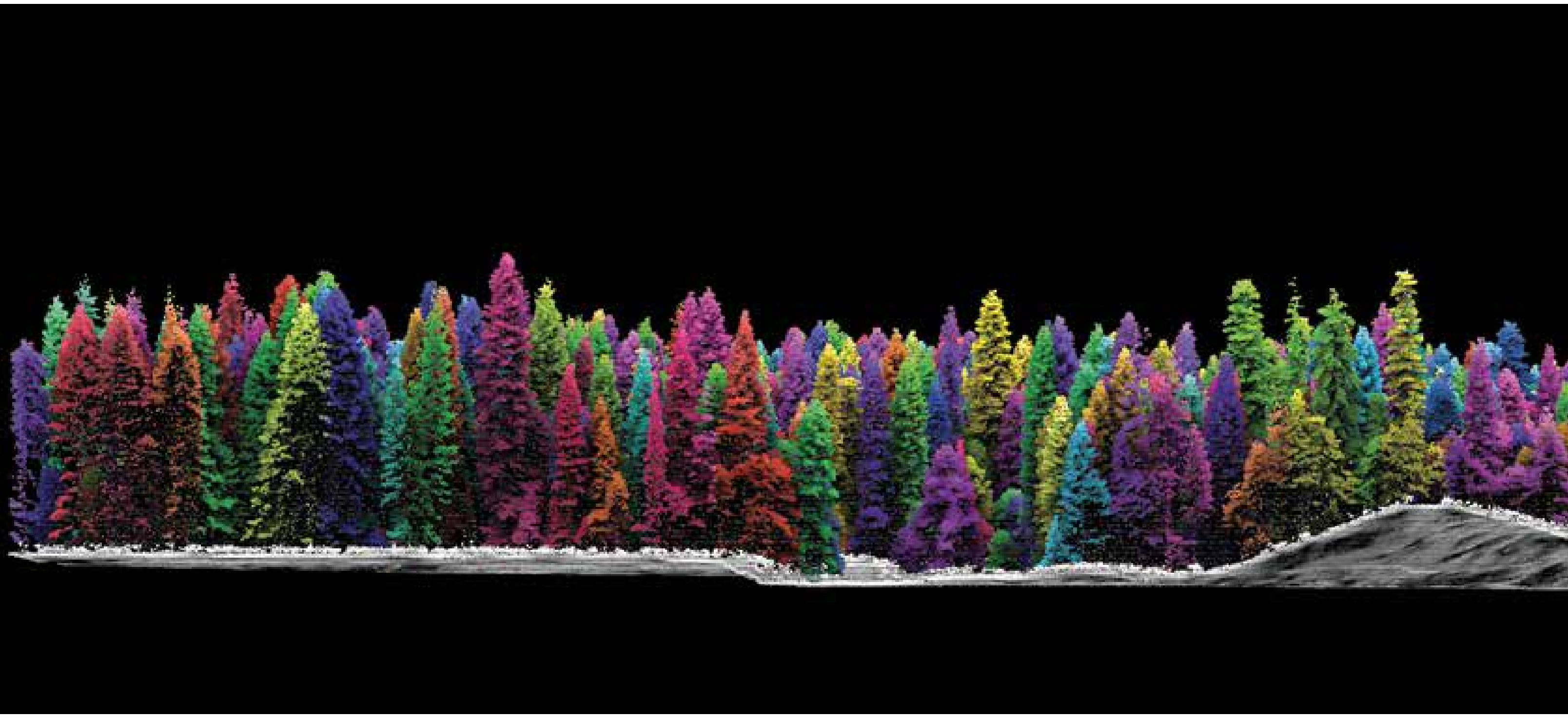
For much of the 19th and 20th centuries, forest management efforts in the United States were focused on fire suppression. The rationale was that by preventing fires, forest management agencies could protect natural resources and wildlife, drive economic growth in the timber industry, and safeguard the lives and livelihoods of those living nearby.

However, in the 1960s, fire ecology research at the University of California, Berkeley shined a light on the connection between regular fires and forest health for many forests in the arid western United States. In this work, researchers found that areas burned by fires under nonextreme weather conditions ultimately became more resilient and resistant to future burning. With less flammable material for subsequent fires to burn, these fires were prevented from burning as intensely and moving as rapidly over the landscape as they otherwise would have.

As a result of this research, in the early 1970s, forest managers in Sequoia and Yosemite national parks in the Sierra Nevada of California were among the first to introduce prescribed burns and to allow lightning-sparked wildfires to burn in their jurisdictions as part of a fire benefit program. In doing so, they sought to return these forests to a healthy cycle involving frequent fires that had existed for centuries before managers first sought to suppress all fires in the 19th century.

Much of this early fire ecology knowledge was gained through field studies. Research teams measured conditions on the ground, then extrapolated from these small plots to estimate likely conditions across vast reaches of parkland as they developed management plans. From there, forest managers embarked on strategic thinning initiatives or set managed, pre-

Forest structure, as seen in images like this 2019 lidar point cloud collected in Yosemite, can be used to assess fire risk and analyze other aspects of a forest. Credit: NV5 Geospatial



scribed fires to improve forest health and resilience.

The success of this approach became especially evident during the 2013 Rim Fire, which started in California's Stanislaus National Forest but quickly spread to neighboring Yosemite. The fire caused less damage in Yosemite where it entered forests that had been subjected previously to lower-severity burns. In these areas, there was less undergrowth and thus smaller fuel loads, which resulted in lower-intensity fires that burned along the ground rather than laddering up into the crowns of large, old-growth trees.

Measuring the Whole Forest

Scientists' ability to study Yosemite's forests both on a broader scale and in more detail began to change in 2010. From 2010 to 2011, Watershed Science (now NV5 Geospatial) used its airborne lidar instruments to image and measure a total of 64,800 acres (26,200 hectares) of Yosemite National Park's forests, in research initiated by James Lutz, now at Utah State University, and Malcolm North of the U.S. Forest Service's Pacific Southwest Research Station. These lidar data—collected at a high density of about 100,000 measurements per acre (247,000 per hectare) across the full study area—provided a census of the 3D structure of vegetation and the ground below.

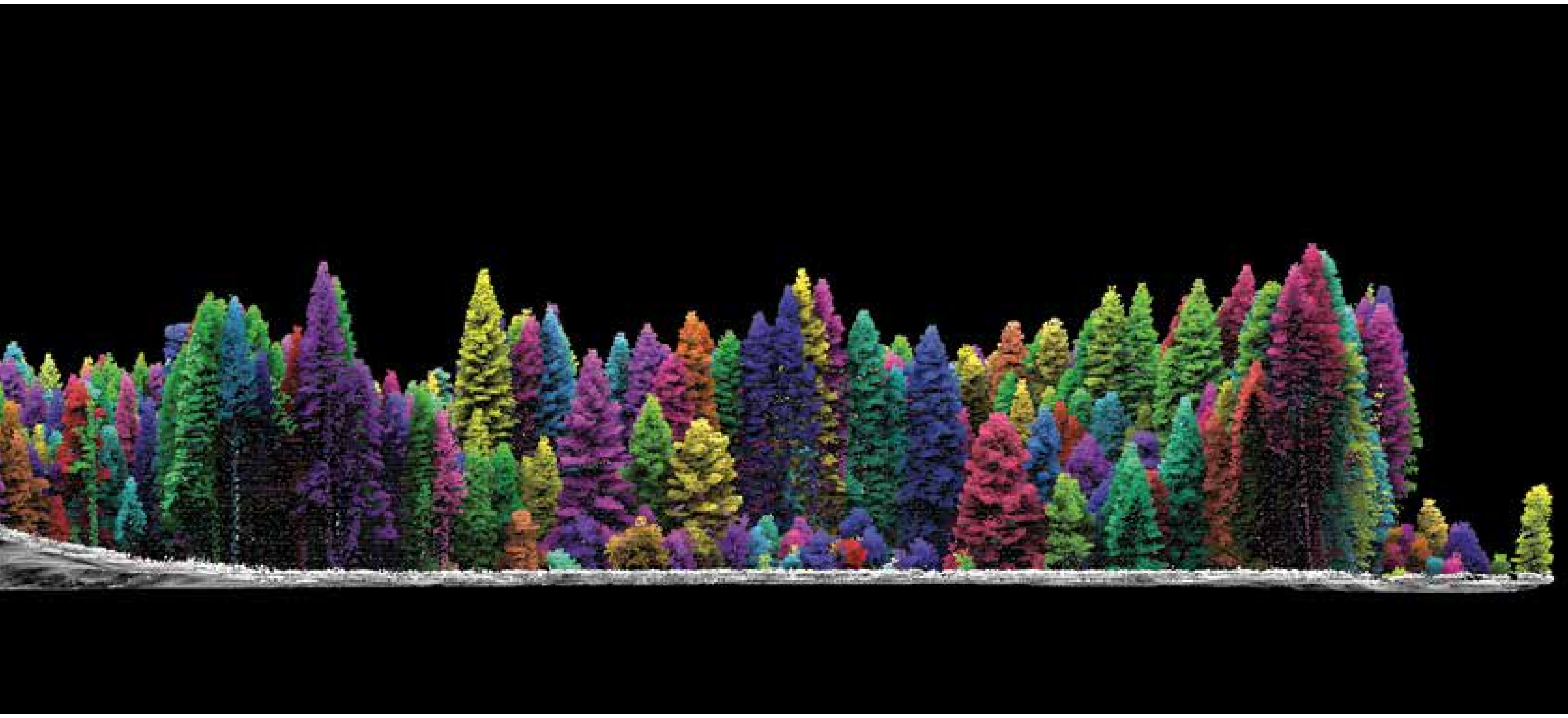
These data sets, supplemented by a larger lidar acquisition in 2013 following the Rim Fire that year, enabled numerous and varied studies focusing on the overall effects of fires, their impacts on habitat for critical species and on hydrology, and guidelines for managers seeking to improve the resilience of other Sierra Nevada forests to wildfire [*Kane et al.*, 2013, 2014, 2015].

Lidar-based studies added nuance and breadth to prior research and observations by ecologists and forest managers on the effects of fire.

The first of these studies, led by one of the coauthors of this article, used the lidar data to examine the effects of fire across several forest types [*Kane et al.*, 2013]. These forest types included stands (groups of trees) that had experienced a range of fire histories, from stands where fires had been suppressed for a century to others burned as many as three times under the restored fire regime enacted by the park's managers since the 1970s.

Key to these studies was the concept of the resulting burn severity. Wildfires naturally burn at different intensities over different areas. Burn severity describes the effects of fire on soils and vegetation and is commonly classified as low (only material on the ground burned), moderate (a portion of trees were also killed), or high (most to all trees were killed). Burn severity also has varying impacts on soil structure, permeability, organic matter, and ability to support regeneration of the forest. Generally, these severities are estimated from multispectral images collected by satellites, such as NASA's Landsat, by analyzing ratios of spectral bands in the images that indicate values corresponding to the removal of green vegetation and organic matter from soils.

The lidar-based studies added nuance and breadth to prior research and observations by ecologists and forest managers on the effects of fire. For example, previous fieldwork had suggested that low-severity fires removed fuels primarily on the sur-



Understanding forest structure and responses to fire is more important than ever, considering how the incidence and intensity of forest fires are rising across much of the planet.

face but caused little change to the structure of the forest canopy above. However, the lidar measurements indicated that low-severity fires did a better job at thinning both underbrush and dead and unhealthy trees than had been thought, suggesting that these burns may be effective at improving forest resilience.

Forests that have survived one or more fires tend to be more resilient to subsequent fires. A key trait of these forests is that previous fires leave a pattern of surviving individual trees or small clumps of trees interspersed with openings and gaps. Reconstructions of forests from more than 100 years ago, before managers began suppressing fires, have shown that these conditions were widespread among the U.S. West's drier forests, including in Yosemite, and were key to forests thriving in a regime of frequent fires [*Collins et al.*, 2011; *Larson and Churchill*, 2012; *North et al.*, 2022]. This pattern reduced the fuel load available and created a web of natural firebreaks, increasing the probability of lower-severity fires. However, fire suppression over many decades allowed trees to fill in the openings, creating dense stands prone to intense fires that threaten forest survival.

The historic tree clump and opening patterns were created by natural fires burning occasionally over centuries. Could fires burning today in vastly changed forests re-create these key patterns? With the lidar data collected in the early 2010s, we mapped patterns of trees and openings in Yosemite's forests. The results revealed that where multiple fires had burned the same locations—reflecting a successful restoration of the frequent fire regime—these key patterns were present. Unexpectedly, we also found that even the first fire to burn a location in a century, if it burned under moderate weather and caused low to moderate burn severity, could re-create clump and opening patterns reminiscent of historic fire-resilient forests. This finding strongly supports the idea that using prescribed fires when weather conditions are not too dry can help restore forests and make them more resilient to future fires.

The Next Generation of Lidar-Based Studies

Until 2019, only about a third of Yosemite had been measured with lidar. In 2019, NV5 Geospatial, funded by the U.S. Geological Survey (USGS) and the Yosemite Conservancy, conducted a comprehensive aerial survey across all of Yosemite and some adjacent areas. This survey, collected using the latest generation of airborne commercial lidar technology, provides more detailed measurements, particularly of vegetation structure, than the earlier surveys did. The project was completed as part of USGS's 3D Elevation Program, the objective of which is to meet growing needs for high-quality topographic data and for a wide range of other 3D representations of the nation's natural and constructed features. The new data, for example, offer clearer looks at canopy structure and enable better mapping of fuel ladders (fuel that carries fire from low-growing vegetation into the tree canopy) and snags (dead trees). The new survey showed that forests in Yosemite have changed considerably even since they were first measured with lidar less than a decade earlier. Between 2013 and 2019, 354 fires burned 132,205 acres (53,500 hectares) of its forests—sometimes for the second or third time.

The Rim Fire caused less damage in Yosemite where it entered forests that had been subjected previously to lower-severity burns.

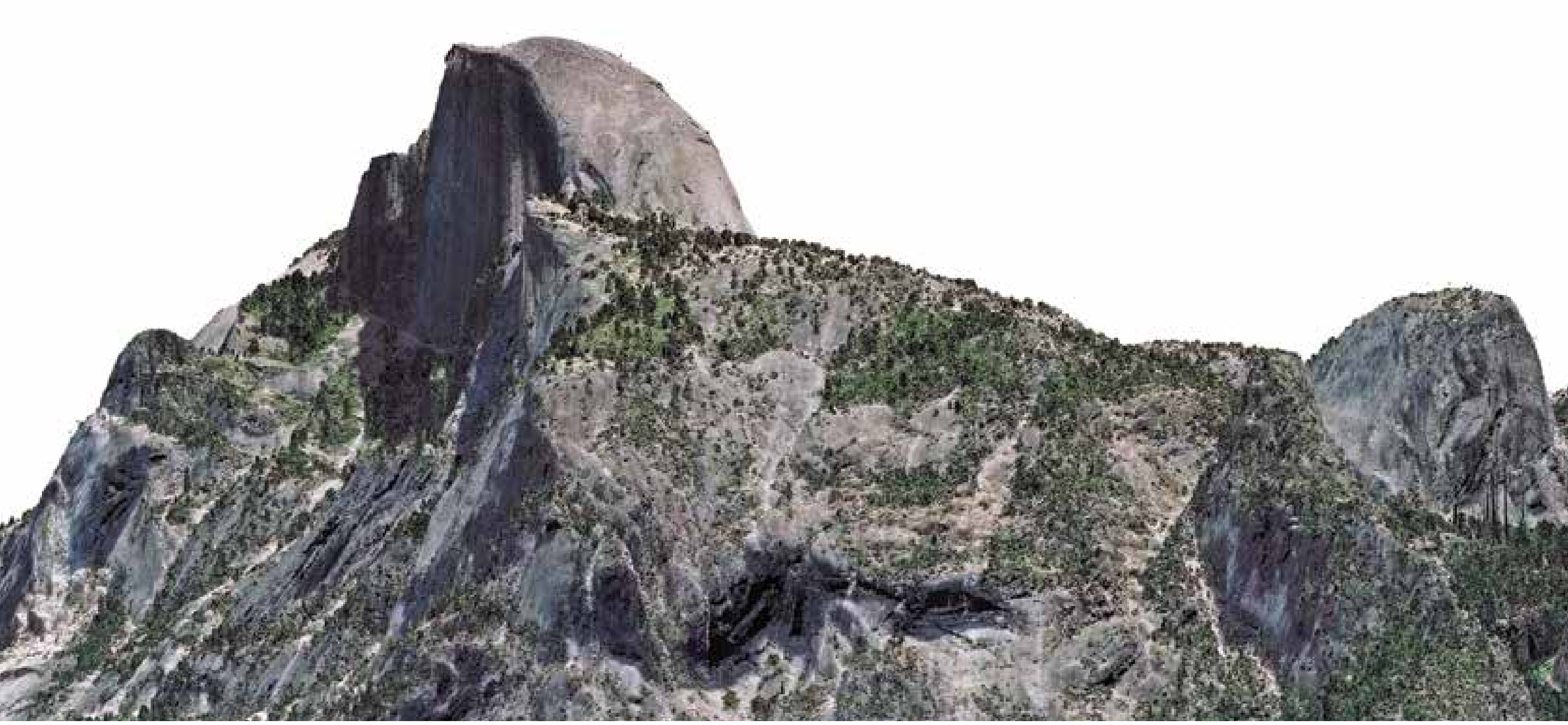
More important, the recent data document how the devastating multiyear drought resulted in the death of a large fraction of the park's trees in several key forest types like ponderosa pine and mixed-conifer forests, changing the character of these forests. The dead trees constitute a huge, unprecedented pulse of fuel that will feed future fires. Instead of being restorative, future fires fed by this massive fuel load could be devastating, akin to the 2020 Creek Fire that burned under similar conditions farther south in the Sierra Nevada.

The new lidar data have been processed and recently been made available to Yosemite's managers and to researchers. We are beginning to work with the park's managers to apply the new measurements to assess conditions across the entire park. Data from the earlier lidar flights will provide an important historic sample that will allow us to examine the intervening changes in detail.

Benefits Beyond Forests

The utility of lidar extends beyond fire management applications. For example, the earlier round of Yosemite lidar data was also used in a study of California spotted owl habitat. A key question that field studies had not been able to resolve was whether these threatened birds require a high density of canopy cover—a condition that would encourage more severe fires—throughout their ranges to survive. When we combined the Yosemite lidar data with lidar data from other Sierra Nevada forests, we showed that these owls require dense canopy cover only around their immediate nesting sites [*North et al.*, 2017]. This finding can help forest managers safely thin forests farther from owls' nests, thereby improving the forests' resilience to future fires and drought while maintaining safe habitat for the owls.

Droughts and fires not only jeopardize forest health and wildlife habitat; they alsostress water resources for residents in the western United States. The depth and location of snowpack often affect water availability, which in turn can create shortages for residents. Lidar can help water managers in the Sierra Nevada, the Rocky Mountains, and other snowpack-influenced regions measure snow depth across large areas, and when it is combined with airborne hyperspectral imagery that gives information about the reflectivity of the snow (albedo),



The well-known granite outcrop of Half Dome and its surroundings in Yosemite National Park are shown in this 2019 lidar image, with tree cover in green. Credit: NV5 Geospatial

Recent data document how the devastating multiyear drought resulted in the death of a large fraction of the park's trees, changing the character of these forests.

the combined data set provides information about the quantity of water stored in the snowpack. By comparing changes in snowpack over time within watersheds, rates of snowmelt can be estimated.

These data help managers regulate releases from reservoirs that provide water to urbanized areas in California, Colorado, and elsewhere. If water managers underestimate snowmelt and retain more water, their reservoirs could be overtopped, requiring rapid releases to avoid catastrophic damage. Alternatively, if they overestimate snowmelt and release too much water, they may not have enough to supply communities during drier times of the year.

Seeing the Forest *and* the Trees

Forests play many vital and stabilizing roles on our planet, including in mitigating climate change by moderating temperature and humidity and as prominent parts of Earth's carbon and water cycles. They are also home to diverse species of animals and plants, they contribute to economies through timber production and tourism, and they are widely used for recreation.

Understanding forest structure and responses to fire is more important than ever, considering how the incidence and intensity of forest fires are rising across much of the planet. Improving our understanding will help us to ensure the health of these important resources, prevent out-of-control fires that threaten lives and livelihoods, and preserve endangered wildlife habitat.

Lidar's capabilities to measure vegetation structure in detail across wide areas are shifting the paradigm of how forests are analyzed, and the technology is now being adopted as a foundational data collection method for forest management in the same way aerial photography was more than half a century ago.

Since lidar's initial use to study Yosemite just over a decade ago, lidar data have already revealed many new ecological insights that are changing not just how forestry practices are implemented but also how we see the forest. Scientists and forest managers are looking at how individual trees, rather than management units (i.e., stands of trees spread across 5–100 acres (2–40 hectares)), respond to and interact with climate and their local environment. This granular level of detail tells us much more about the processes occurring in forests and will help us make sustainable and wise decisions about resources that are essential for our long-term survival.

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Food Deficits in Africa Will Grow in a Warmer World

A farmer tends cattle pulling a plow through soil in Hawzen, Ethiopia. Even with increases in sustainable farming practices and water storage, new research projects major food deficits for much of Africa in the coming decades. Credit: Rod Waddington/Flickr, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Africa has one of the world's fastest rates of population growth. Growth models project that the continent's current population of about 1.3 billion people will nearly double to 2.5 billion by 2050—and it's likely to keep growing beyond that.

At the same time, malnutrition is widespread in Africa—21% of the population faces food insecurity—and the continent is especially vulnerable to climate change. Warmer regions are already experiencing desertification, and areas of low agricultural productivity are susceptible to climate shocks from adverse weather, drought, flooding, and erratic rainfall. The combined effects of population growth and climate change raise a serious question for the continent: How will Africa feed its growing populace in increasingly unfriendly conditions?

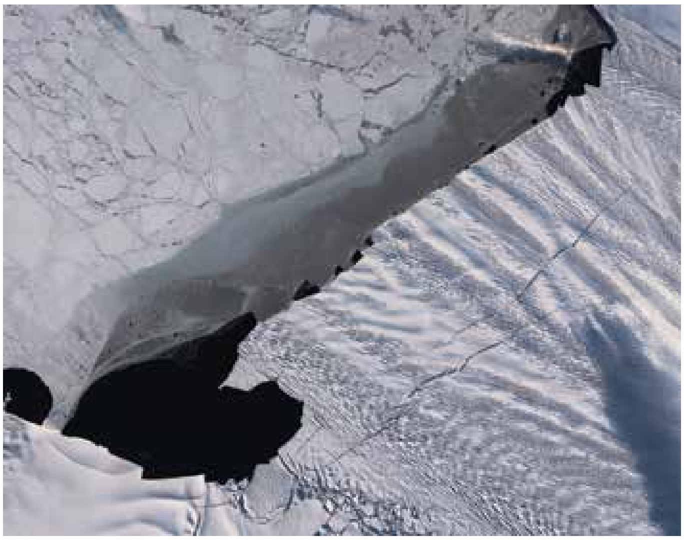
Beltran-Peña and D'Odorico applied the results from agrohydrological, climate, and socioeconomic models to assess food self-sufficiency and climate vulnerability for 49 African countries under a scenario in which the global average temperature is 3°C above preindustrial levels by later this century. They found that under a 3°C warmer climate, Africa will face a severe mismatch between population size and food autonomy. By 2075, food production in Africa will be able to feed only 1.35 billion people out of an estimated 3.5 billion—a finding that already accounts for increased agricultural productivity through improved irrigation and sustainable practices.

Under this climate scenario, African nations will have to expand cropland and rely more heavily on food imports. Both approaches come with downsides: Cropland expansion carries potentially disastrous ecological ramifications, whereas reliance on imports would make Africa more susceptible to volatility in global food prices. The analysis indicated that eastern and western Africa will have the most significant import needs.

The research also suggested steps to address the grim forecast. Increasing the proportion of plant-based foods consumed and improving water storage—particularly in arid regions—can help mitigate the increasing food insecurity, for example. In addition, halving current food loss and waste rates could bolster domestic food production and feed an additional 130 million people. Nevertheless, the researchers note, these solutions will not eliminate projected food deficits on the continent.

The second of the United Nations' Sustainable Development Goals is to end hunger and malnutrition. This research suggests that this goal may not be feasible in Africa under the current emissions and warming paradigm. (*Earth's Future*, https://doi.org/10.1029/2022EF002651, 2022) **—Aaron Sidder,** ***Science Writer***

Melting Below the Pine Island Ice Shelf Minds the Gap



Two large cracks in the Pine Island Ice Shelf appear in this image taken by the Copernicus Sentinel-2 satellite on 14 September 2019. Credit: European Space Agency, CC BY-SA 3.0 IGO (bit.ly/ccbysa3-0)

The Pine Island Ice Shelf (PIIS) is the seaward extension of Pine Island Glacier, a large and rapidly retreating glacier that drains part of the West Antarctic Ice Sheet. Beneath the floating PIIS is a seafloor ridge that narrows the gap through which relatively warm seawater from the open ocean can flow in and circulate beneath the ice shelf.

This narrowing helps protect the underside of the PIIS on the landward side of the seafloor ridge from melting. But in the past decade, the ice shelf has seen large amounts of calving, causing the ice front to retreat toward the continent and approach the ridge—and the calving shows no sign of slowing.

Bradley et al. investigate how calving affects melting of the PIIS. The team used a high-resolution ocean model to simulate ocean circulation and melt rates below the ice shelf, modeling and comparing results from both an idealized setting meant to represent the most important features of the ice shelf and ridge and real-world conditions that closely match the site characteristics for the PIIS.

They found that ice shelf melt rates are sensitive to the thickness of the gap between the PIIS and the seafloor ridge, suggesting that the changing geometry of the gap with a retreating ice front leads to strengthening of seawater circulation beneath the ice. As calving from the PIIS ice front continues, the melt rate will increase linearly, the team found, becoming 10% higher than it is now by the time the ice front retreats to the ridgeline.

The researchers say the results highlight that calving could be an important contributor to melting of the West Antarctic Ice Sheet. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2022JC018621, 2022) **—Sarah Derouin,** *Science Writer*

Fiber Optics Opens New Frontier for Landslide Monitoring

Reservoirs provide water storage, hydropower, and recreation for local communities. However, adding a reservoir can also significantly change a landscape's geological conditions and usher in new and unpredictable hazards, most notably, landslides. Understanding the factors that drive reservoir landslides is paramount to maintaining reservoir infrastructure and public safety.

In a recent study, *Ye et al.* introduce a new fiber-optic nerve system (FONS) to monitor and study reservoir landslides. The authors designed, implemented, and installed their FONS, which provides real-time, high spatial resolution data at centimeter scales to monitor the ancient Outang landslide in China's Three Gorges Reservoir region. The landslide has a volume exceeding 90 million cubic meters and migrates 100–500 millimeters per year.

The ancient Outang landslide, on slopes of China's Three Gorges Reservoir, is a new test site for subsurface monitoring that provides real-time data on the causes and triggers of reservoir landslides. Credit: Le Grand Portage/Wikimedia, CC BY 2.0 (bit.ly/ccby2-0)

The setup deploys separate fiber-optic cables for each monitored variable—subsurface temperature, moisture, and strain. The sensors are bundled into a 110-millimeter-diameter borehole extending more than 40 meters below the surface. The array wirelessly transmits metrics on subsurface conditions to a data server at the surface, which allows the researchers to monitor landslide kinematics, hydrological transport, and sediment retention.

With data from the FONS, the authors confirmed the rear slope's main and secondary slip surfaces. In addition, they determined that short, high-intensity rains had a more significant effect on landslide mechanics than steady rains that dropped the same amount of moisture on the surface. This finding contradicted the hypothesized relationship between rainfall and landslide movement.

The new underground detection system opens possibilities for integrated hazard monitoring and offers critical insights into reservoir landslides' thermohydromechanical causes, triggers, and mechanisms, the researchers said. Future applications could combine the system with satellite, aerial, and surface sensors to look comprehensively at geohazards. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL098211, 2022) **—Aaron Sidder,** *Science Writer*

Deep Earthquakes Suggest Well-Hydrated Mariana Subduction Zone

On the surface, subduction zones manifest as oceanic trenches, the deepest of which is the Mariana Trench in the Pacific Ocean. One notable feature of many trenches is their outer rise, a shallow bulge on the outskirts of the trench that forms as the subducting plate compresses and kinks. This compression and deformation can result in the creation of faults. These cracks in the seafloor are an important vector for delivering water to the mantle at subduction zones. However, high-resolution details about the structure of outer rise faults have not yet been produced.

Chen et al. explored the outer rise faulting around the Mariana Trench using data from 12 ocean bottom seismometers placed around the Challenger Deep, the trench's deepest point, between December 2016 and June 2017. The researchers then applied machine learning–based EQTransformer software to the seismic data, which led to the identification of 1,975 earthquakes that occurred in the region during the first half of 2017.

The locations of these earthquakes were then pinpointed using two modeling softwares, Hypoinverse and HypoDD. The level of seismic activity across the outer rise region was strongly variable, the authors found. One particular cluster of events extended to a depth of 50 kilometers, deeper than previously suspected for the region.

The 50-kilometer depth indicates that this subduction zone is well hydrated. These results not only suggest that water input at the southernmost Mariana subduction zone is much higher than previously estimated but also provide important insights into subduction zone dynamics, the researchers said. (*Geophysical Research Letters*, https://doi.org/10.1029/2022GL097779, 2022) **—Morgan Rehnberg,** *Science Writer*

Amazon Basin Tree Rings Hold a Record of the Region's Rainfall

To assemble records of past rainfall in the Amazon, scientists collected tree ring samples from multiple sites in Bolivia as well as from this montane forest near Cuyuja, Ecuador. Credit: Jessica Baker

The Amazon basin contains the world's largest rain forest, famous for its rich biodiversity and importance in the world's oxygen and carbon cycles. It also has an outsized influence on water cycles in South America and beyond. Understanding how climate change is affecting Amazon hydrology is thus a key priority for climate researchers. However, modern measurements of the region's annual rainfall don't provide the historical context needed to explain a recent uptick in wet-season precipitation.

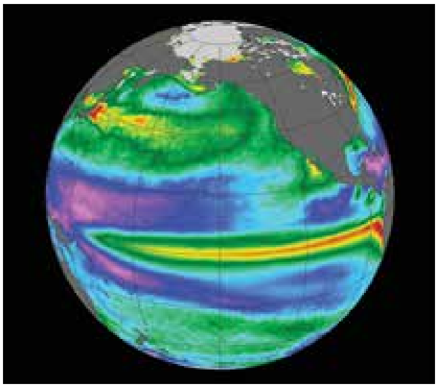
Baker et al. use more than 200 years of oxygen isotope data from tree rings as a window into the region's hydrological past. Oxygen isotopes can serve as a proxy for historic rainfall amounts because heavier isotopes are more likely to get flushed out of the atmosphere in precipitation in years of greater rainfall. That means rings formed in years with less rainfall should have a higher proportion of heavy oxygen isotopes compared with wetter years.

The data set assembled in this study is the longest oxygen isotope record from the Amazon basin to date and one of the longest such records for any rain forest in the world. To create it, researchers collected tree ring cores and disks from more than 50 trees growing in lowland rain forest in Bolivia and montane forest in Ecuador. Samples collected from Ecuador provided data from 1799–2012, whereas data from Bolivia samples spanned 1860 to 2014.

The records from the two locations matched each other closely, indicating that the trees captured large-scale climate signals not confined to the regions where the trees were. Oxygen isotope fluctuations from year to year also corresponded well to modern hydrological data, indicating a reliable record of past change.

Because precipitation and sea surface temperatures in the region are linked, the researchers also compared their findings with reconstructed sea surface temperature records. Their data set indicates that annual rainfall in the Amazon decreased as sea surface temperature rose between about 1800 and 1950. After that, the relationship between the two became shakier. In the past couple of decades, the trend reversed, a finding consistent with modern records showing that the Amazon hydrological cycle has amplified in recent years. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2022JG006955, 2022) **—Rachel Fritts,** *Science Writer*

Spatial Scale Shapes How Ocean and Atmosphere Influence Climate



Data from the J-OFURO3 satellite product show the intensity of monthly sea surface temperature variations across the global ocean. Red colors indicate sea surface temperature swings from month to month that are typically larger than 1.5°C; dark blues and purples indicate variations that are typically smaller than 0.5°C. Credit: NCAR; data from the J-OFURO3 satellite product

Knowing the scales at which the sea and atmosphere influence climate is essential for interpreting climate modeling results. Previous work suggests that ocean currents dictate heat exchange at scales ranging up to 500–700 kilometers. Yet the influence of ocean currents and weather varies across time and space, and the point at which oceans cede control to weather remains poorly understood.

In a recent study, *Laurindo et al.* investigated the influence of ocean currents and weather in driving heat exchange between air and sea. They focused on two crucial climate-shaping variables: sea surface temperature and turbulent heat flux. The study concentrated on the midlatitudes in the Pacific Ocean.

The authors analyzed the spectra of satellite data from the Japanese Ocean Flux Data Sets with Use of Remote-Sensing Observations (J-OFURO3) research project. They combined these data with comprehensive climate simulations, including a high-resolution version that resolves ocean currents at tens of kilometers and a low-resolution version that depicts currents over hundreds of kilometers.

The team found that weather and ocean currents drive variability in sea surface temperatures over similar timescales, ranging from 2 months to several decades. The results suggest that at midlatitudes, oceans can cause variability in sea surface temperature and turbulent heat flux over as much as a 2,000-kilometer range. At larger scales, however, the atmosphere exerts a stronger influence.

According to the authors, this research advances the understanding of air-sea interactions and the importance of scale in the air-sea relationship. The results should further clarify interpretations of climate modeling, as well as causality in the Earth system as a whole. (*Journal of Geophysical Research: Oceans*, https://doi.org/10.1029/2021JC018340, 2022) **—Aaron Sidder,** *Science Writer*

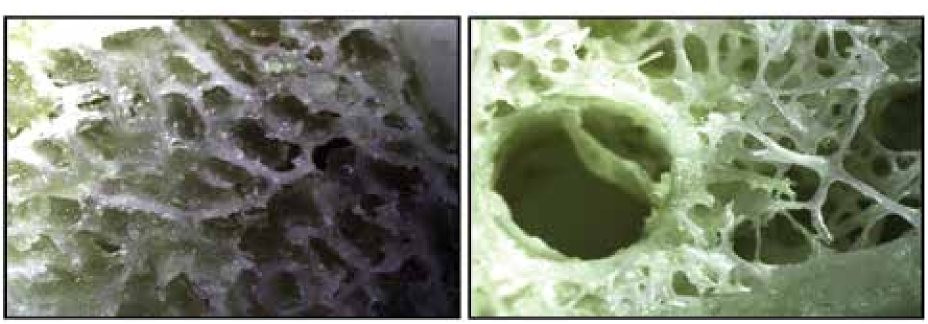
Higher Lead Concentrations Found in Diseased Bones

Among the world's population over age 60, chronic illnesses like the degenerative bone disease osteoporosis continue to become more common. Trace elements of chemical impurities in bones might play a role in the development of osteoporosis, but this role is currently poorly understood. Identifying which elements have little effect on bones and which might contribute to degeneration can help researchers better understand and treat osteoporosis.

To gain insight into the relationship between trace element impurities and osteoporosis, *Coyte et al.* selected 16 trace elements and analyzed their prevalence in samples from 58 patients who underwent hip replacement surgery. Of these patients, who ranged in age from 41 to 100, 29 were diagnosed with osteoporosis and 29 had osteoarthritis, a degenerative disease that affects cartilage but not bone. Researchers tested cortical bone (hard outer layer) and trabecular bone (spongy inner layer) in all samples. Element concentrations in the outer bone result from long-term accumulation, whereas the concentrations of trace elements in the inner bone can change over time.

Of the 16 trace elements tested for, only lead was found in significantly higher concentrations in the outer bone samples of osteoporosis patients compared with osteoarthritis patients. This indicates that environmental lead that individuals are exposed to early in life can accumulate in the body, possibly weakening bone structure later in life. In the inner bone samples, the trace elements chromium and scandium were comparatively more abundant in osteoporosis patients.

The researchers caution that this study cannot specify whether any of the concentration differences detected are a cause or effect of osteoporosis. They suggest that future studies could untangle these correlations and delve deeper into interactions between trace elements to develop better-targeted treatments for this disease. (*GeoHealth*, https://doi.org/10.1029/2021GH000556, 2022) **—Rachel Fritts,** *Science Writer*

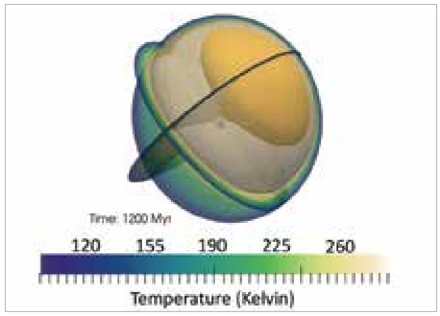


Researchers analyzed bone samples from patients with osteoarthritis (left) and osteoporosis and discovered that people with the latter have higher concentrations of lead in their bones. Credit: Tom Darrah

Convection May Explain Ceres's Missing Craters and Strange Crust

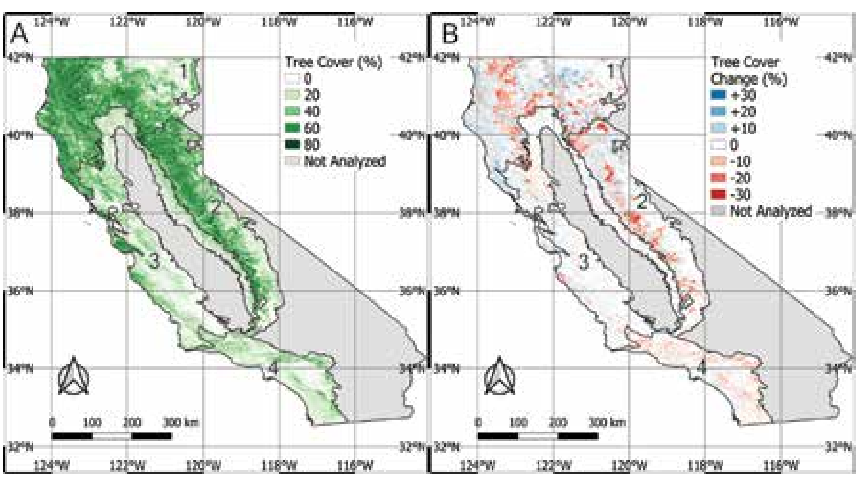
The Dawn mission discovered an unexpectedly young surface on Ceres, an ice-rich dwarf planet and the asteroid belt's largest asteroid. The absence of ancient large impact basins and the presence of regions of thickened crust, large-scale fractures, and hemisphere- scale variations in gravity indicate a possible role for solid state convection in reshaping the crust. However, absent tidal heating, a long- lived source of energy that might drive such resurfacing has been unclear.

King et al. show that sufficient heat can be generated simply by radioactive decay in certain geophysical regimes in which transient asymmetric upwelling sets up degree-one—that is, hemispherical—convection. Small initial heterogeneities in temperature lead to long-term convective consequences. This process may also be active on other small bodies, perhaps explaining hemisphere-scale resurfacing and tectonics on icy moons in the outer solar system. (https://doi.org/10.1029/2021AV000571, 2022) **—Bethany Ehlmann**



This cross-sectional snapshot shows the simulated 3D structure of Ceres's interior temperature at 1.2 billion model years in one model run with radiogenic heating, convection, and a small perturbation in interior boundary conditions. By half a billion years in the model, a convective instability has developed in the form of hot material moving from the deep interior toward the surface in just one hemisphere, a temperature asymmetry modeled to persist for approximately 2 billion years. Credit: King et al.

The Burning Problem for Natural Climate Solutions



Maps of California's (a) forest cover in 1985 and (b) change in forest cover from 1985 to 2021 show widely distributed changes, with widespread losses and gains concentrated more in northern parts of the state. These losses reflect the roles of fire, dieback, and land use change, as well as relatively slow regrowth following fires. Numbers 1–4 on the maps refer to different ecoregions in the state. Credit: Wang et al.

Natural climate solutions (NCSs), the uptake of carbon from the atmosphere by ecological processes to mitigate climate change, are a topic of intense interest. They are, for the most part, "no regrets" solutions that have additional benefits, particularly when an ecosystem's natural biodiversity and function are protected. NCSs depend on the health and stability of ecosystem carbon stores, which are globally under threat from a combination of land use and climate change. The tropics, which have long been a sink with uptake more than balancing deforestation sources, may be transitioning to becoming a net source. A growing body of literature shows that warmer and drier conditions similarly reduce soil carbon storage, all factors putting NCSs in ecosystems at risk.

Wang et al. show a dramatic case study using historical remote sensing and inventory data. The state of California has ambitious plans for NCSs (bit.ly/CA-nature-based-solutions), but this study shows that patterns of land use, drought, and wildfire put these plans at risk. The authors demonstrate that California has lost approximately 7% of its forest cover since 1985, with losses due to fire exceeding gains and more than balancing regrowth after fire. Losses were greater in the warmer regions of the state and gains were more frequent in the cooler regions, suggesting that continued warming will put additional regions at increased risk. The results show the fast out (dieback and fire) and slow in (forest reestablishment and growth) dynamics characteristic of the land carbon cycle.

California provides a cautionary tale of risks to NCSs but also highlights opportunities for management to mitigate the risks. (https:// doi.org/10.1029/2021AV000654, 2022) **—David Schimel**

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ASSISTANT PROFESSOR IN EARTH AND PLANETARY SURFACE PROCESSES

The Department of Earth and Space Sciences, in the College of the Environment at the University of Washington, is soliciting applications for **two permanent, full-time, 9-month, tenure-track assistant professors** in Earth and planetary surface processes.

POSITION 1: Assistant Professor in Geomorphology
We seek a geomorphologist who will build a strong field-oriented research program. Areas of focus could include but are not limited to landscape evolution and dynamics, fluvial and watershed processes, or cryosphere geomorphic processes. Contributions to interdisciplinary research and teaching in areas such as geologic hazards, field geology, environmental sustainability, or preparation for the professional workforce are desirable.

POSITION 2: Assistant Professor in Earth and Planetary Surface Processes
We seek applicants in Earth and planetary surface processes, broadly defined. Areas of focus could include but are not limited to weathering and soil-forming processes, biogeochemical cycling, and landscape evolution on Earth and/or other planets. Contributions to interdisciplinary research and teaching in areas such as planetary sciences, remote sensing, geobiology, or critical zone research are desirable.

All University of Washington faculty engage in teaching, research and service. Successful candidates will be expected to build vibrant and externally funded research programs that contribute to science of global significance. For both positions, we value the ability to quantify processes and make observational or theoretical advances specific to the surface and near-surface environment. The successful candidates will teach within the core Earth sciences curriculum at both the undergraduate and graduate levels and will demonstrate a commitment to working collaboratively with other faculty and to mentoring students from a wide range of disciplines, cultures and academic backgrounds.

The Department of Earth and Space Sciences includes 35 research and teaching faculty, 90 graduate students, and 200 undergraduate majors. Opportunities for interdisciplinary collaboration exist within the department, as well as with other units at UW.

GMCS

GMCS POSTDOCS AND GRADUATE STUDENT POSITIONS

Postdoc and **graduate student** positions are available in theoretical, computational, and experimental geomechanics for study associated with the new center on Geo-processes in Mineral Carbon Storage (GMCS), funded through the Energy Frontier Research Centers (EFRC) program by the Office of Basic Energy Sciences, US Department of Energy. The objective of GMCS is to develop an understanding of the key geo-processes, occurring across multiple scales, that is necessary to achieve a successful mineral carbon storage operation. This will require cohorts of engineers and scientists, from across the spectrum of geomechanics, geochemistry, porous media flow, reactive transport, and sensing technologies, to work in concert towards the common mission of developing the fundamental science and engineering capability that will lead to realizing the full potential for permanent subsurface storage of CO2 via mineralization.

Researchers will (i) contribute to the theoretical modeling of crack propagation driven by reactive fluids, considering dissolution and precipitation mechanisms; (ii) conduct numerical simulations to assess the evolution of the transport properties of a fractured porous rock caused by injection of a reactive fluid; and (iii) implement a laboratory setup and perform experiments to study the poromechanical and ultrasonic properties of specimens subjected to the flow of water-dissolved CO2. The laboratory facilities supporting the work include the Waves & Imaging Laboratory (**https://bojanguzina.org/waves-imaging-lab/**), the W. David Lacabanne Rock Mechanics Laboratory (**https://cse.umn.edu/cege/research-facilities-civil-engineering-building**), Earth Sciences X-ray Computed Tomography Laboratory (**https://xraylab.esci.umn.edu**), and Porous Media Flow Visualization Laboratory (**https://kang-research-group.esci.umn.edu**).

Successful candidates for the postdoc positions should have a PhD in applied mathematics, civil engineering, earth sciences, or a related field. The initial appointment is for one year and is renewable for up to four years. Expertise in at least one of the following disciplines is expected: fracture mechanics, poromechanics, reactive porous media flow, or wave mechanics; knowledge of geochemistry would be beneficial but is not required. Also of importance are communication skills and ability to work with the senior investigators, other postdocs, and graduate students.

Applicants for the postdoc positions should submit a statement of interest, 2-page CV, and contact information of three references to Emmanuel Detournay **detou001@umn.edu**, Bojan Guzina **guzin001@umn.edu**, Department of Civil, Environmental and Geo- Engineering, and Peter Kang **pkkang@umn.edu**, Department of Earth and Environmental Sciences, University of Minnesota.

Applicants for graduate assistantship positions should complete the UMN graduate school application **https://choose.umn.edu/apply/**

Dear AGU:

Alpacas graze in front of snowcapped volcanoes near Putre, Chile. In March 2022, a interdisciplinary group of scientists spent a month sampling gases, fluids, and sediments from volcanic systems in Chile's Central Volcanic Zone. This work was funded by a National Science Foundation Frontier Research in Earth Sciences grant to Peter Barry, Woods Hole Oceanographic Institution (WHOI).

—**Peter Barry,** WHOI

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