Foreseeing fires

To predict future wildfires, researchers are building models that better account for the vegetation that fans the flames.

Amy McDermott, *Science Writer*

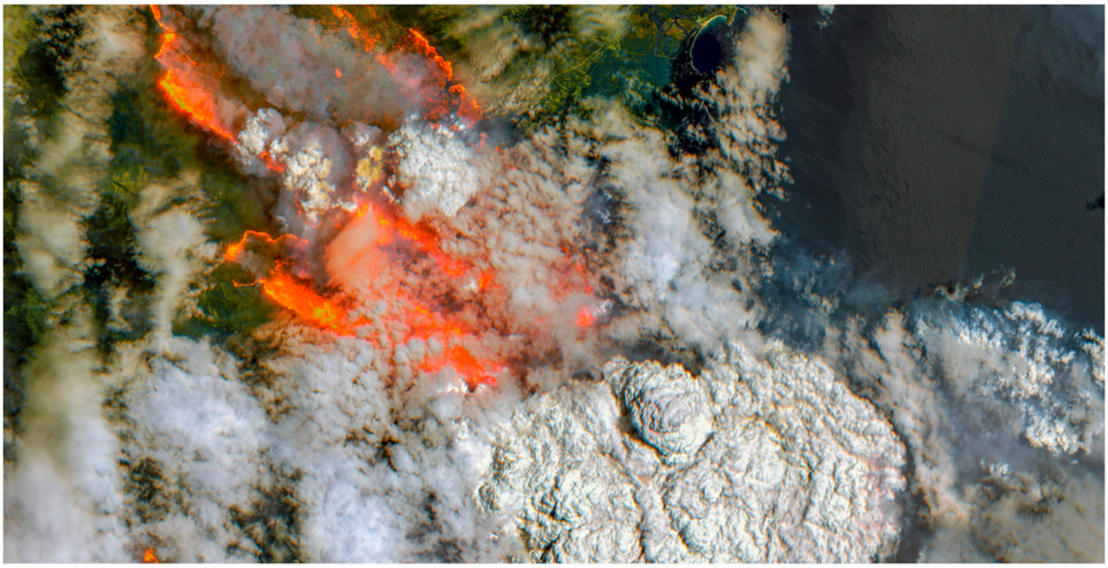
Wildfire ripped through the black spruce forests of Eagle Plains, Yukon Territory, Canada in 1990. Fire came again in 2005. By the time plant ecologist Carissa Brown arrived in the summer of 2007, all but a few trees were dead. Any seedlings that had sprouted after the first fire had burned in the second. Their charcoaled trunks had disintegrated by 2007, leaving open land furred with swishing grasses and tundra shrubs. "It's not what you expect to find up there," says Brown, at Memorial University of Newfoundland in St. John's, Canada (1).

Yukon forests evolved to regenerate quickly after fire. Adult trees died in historical burns every 80 to 150 years, but the heat unsealed the burning trees' small, resinous cones to drop their seeds, kick-starting the next generation. Seedlings that established in the first five to 10 years after a fire took decades to mature.

But now, as the subarctic undergoes rapid warming, some hotter, drier forests are burning much more often, killing immature spruce trees before they have time to set cones. The problem is not limited to the far North. Around the world, wildfires are growing more frequent—as well as larger, hotter, and more destructive (2).

Researchers can no longer look to the past as an accurate predictor of the future. Forests adapted to rare fires may not persist through frequent ones. To predict the size and severity of coming wildfires this century, researchers need more sophisticated models that can account for changing vegetation. They need to know how forests and vegetation will respond to a first fire, because the plants that grow back will fuel the next fire there.

Having those data in hand would allow forest managers to predict how often or how severely a given area



As wildfires become more common and more intense, researchers seek to predict how often or how severely a given location might burn. More and better field data could be key to improving computer models in order to predict fires such as these near Batemans Bay, New South Wales, Australia, which took place in 2019. The image was captured by satellite and includes a mix of natural colors and infrared data. Image credit: Flickr/Copernicus Sentinel/Sentinel Hub/Pierre Markuse.

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Frequent fires dramatically change patches of the landscape in Eagle Plains, Yukon Territory, Canada. Consider the vegetation in the unburned black spruce forest (*Left*) compared with a stand burned about 100 years ago (*Middle*), compared with one burned in 1990 and 2005 (*Right*). Images credit: Carissa Brown (Memorial University of Newfoundland, St. John's, NL, Canada).

might burn. On a global scale, these models could also help inform predictions of the carbon emissions from changing landscapes.

Now, researchers are seeking to ramp up field observations and experiments to help show how resilient forests can be in the face of repeat wildfires. The spate of research, much of it new, is informing computer models to make more accurate fire forecasts. "That's the tip of the spear right now," says forest ecologist Monica Turner of the University of Wisconsin-Madison.

Tiny Worlds in Motion

Computer models are used to estimate how often a given area is likely to burn, how intense the fires will be, and how large or small fires might be distributed across the landscape. More than 60 landscape fire succession models (LFSMs) exist today, operating on timescales ranging from decades to millennia and on geographic scales up to 2 million acres in size (3). A look at how they work reveals both strengths and shortcomings.

One such model, iLand, depicts trees as a landscape of colorful circles on the screen: olive for lodgepole pine, light blue for spruce, and dark blue for subalpine fir. Feed in climate projection data and press play, and iLand runs like a tiny world in fast forward. Circles blink on and off as trees compete for resources, colonizing new areas or dying out in a high-speed simulation of the coming decades.

iLand predicts how forests will shift based on field observations of trees' responses to changing temperature and rainfall, the distance their seeds can disperse, and their rate of photosynthesis, among other factors. Using a simulated plant-covered landscape in combination with the climate data, the model then estimates which forest patches will be hottest, driest, and most fire prone, as well as where there is enough fuel for fire to spread. Although iLand is designed as research software, a forest manager in Yellowstone National Park might plug 50,000 acres into the model, beginning with a current map and climate projections out to 2098, to predict how often a specific area of Yellowstone might burn or where large fires are most likely in general, explains forest ecologist and iLand principal developer Rupert Seidl, at the Technical University of Munich in Germany.

Like most LFSMs, the iLand model makes its fire predictions, in part, by simulating how vegetation will shift across a landscape over time. Some of the factors that determine this have been well studied and modeled for years, explains fire ecologist Robert Keane, who's based at the Missoula Fire Sciences Laboratory in Montana, part of the US Forest Service Rocky Mountain Research Station. Well-modeled factors include tree growth and death in response to changing rainfall, temperature, and sunlight, as well as some pest and insect outbreaks, and drought.

But one key piece of information has been missing: how patches of vegetation recover after a first fire—and a second, and a third. Do forests grow back with the same mix of species in the same locations, or do plant communities undergo fundamental changes between burns? The answers matter, says Keane, because the plants that grow on a burn site after a first fire are fuel for the next fire there. And some trees and shrubs burn hotter and cause more severe fires than others. Prolonged plant recovery times can also create fire breaks on the landscape, he says.

Without good data, some LFSM models have assumed forests are completely resilient to fires, growing back with their original mix of species in their original locations. Others have assumed the opposite, that a forest is not replaced after a severe-enough fire, Seidl says. A wave of new research is using field observations and experiments to find out how vegetation really does change or move, and hence what the models should assume and what the frequency, size, and severity of fires will be long term.

That research includes field work in Yellowstone where ecologist Winslow Hansen led a long-term field experiment published in 2019. Hansen and Turner planted lodgepole pine and Douglas fir seeds in soil plots mimicking the hot, dry, post-fire conditions expected in 50-year projections for the park (4). Most lodgepoles in Yellowstone today grow at cooler, higher elevations than Douglas firs. So the researchers set up their field plots by bringing post-fire soils from high elevations to hotter, low-elevation sites, to test how the

Researchers collect field data in Greater Yellowstone that can help inform landscape fire succession models (LFSMs) and better predict future fire patterns. Image credit: Ann K. Olsson (photographer).

combination of a future hot, dry climate and post-fire soils affected seedlings' ability to establish and grow, Hansen says over the phone from his desk at Columbia University's Lamont-Doherty Earth Observatory in Palisades, NY. The study revealed a 92% reduction in lodgepole pine seedling establishment, compared with forests today, and a 76% reduction in Douglas fir.

"In Yellowstone, lodgepole pine is the major player," Hansen says. "If they can't establish, it's possible the system converts to nonforest rather than a different tree species." Changing the dominant vegetation will likely change the size, severity, and frequency of fires as well as our ability to predict their patterns of occurrence.

It's not just in Yellowstone. A 2019 review of 49 articles published since 2000 tracked seedling density after more than 150 wildfires in the Western United States, including in South Dakota's Black Hills, the Pacific Northwest and Southwest, and the Rocky Mountains. The review echoed Hansen's concerns that new seedlings may not establish after future wildfires, leading many forests to become grassland or scrublands (5). Forest ecologist Jonathan Coop, at Western Colorado University in Gunnison, coauthored a review published in July, analyzing more than 100 studies from western North America and Canada (6). The main takeaway, Coop says, is that "in an era of changing climate and increasing wildfire activity, we really can't count on forests to come back." Climate change itself makes post-fire forest recovery less likely, according to the review, because the hotter, drier conditions can parch and kill those seedlings that do disperse into a burned area.

New Landscape

As Brown hiked the charred Eagle Plains in Canada's Yukon Territory, a landscape that had burned in 1990 and again in 2005, she noted that the forest had been incinerated to the point where "in reburned areas, there was just an absence of anything that had to do with trees."

Black spruce died young there, before they were old enough to drop their tiny black seeds to the forest floor. And although the seeds have a thin brown wing to catch the wind, they're only known to fly about 80 meters, not far enough to reseed hundreds of acres of burned-out forest. Brown began to suspect that the spruce wouldn't recover in Eagle Plains, because there weren't enough new seeds. The grasses and shrubs moving in would become the new normal there, she hypothesized, replacing what had once been endless conifer stands.

To test her suspicions, Brown laid out 0.5-meter-square experimental plots in the summer of 2007 and sprinkled four different kinds of native tree seeds onto some of the plots while leaving others as unperturbed controls. She returned every summer for three years. By 2010, few seedlings had established on the unmodified control plots, whereas many grew on the plots sprinkled with seeds (1). The findings confirmed Brown's hypothesis that without supplemental seeds the Yukon's black spruce forests will probably not regrow after recurrent fires.

Brown coauthored a follow-up study in 2015, using her experimental data from the Yukon in combination with similar experiments from Alaskan black spruce forests that burned in 2004 or 2005. Once again, she found dozens more seedlings on experimental plots than on controls. Similar results in Alaska and the Yukon hint that if fires are too frequent, seed limitation could be widespread for subarctic black spruce forests (7).

If more frequent fires convert boreal forest to grassland, a lot of carbon would be released, with global implications for climate change. High-latitude fires release more carbon per square meter than burns in most other ecosystems, dwarfing recurrent California wildfires, for example, by three to five times the carbon released per unit area. The difference is largely because decomposition is slower in cold northern temperatures, so a thick layer of carbon-rich organic material can build up. Unpublished projections of future fire regimes and greenhouse gas emissions from Earth system scientist Brendan Rogers at the Woods Hole Research Center in Falmouth, MA, suggest that intensifying fires in boreal regions of Canada and Alaska could release substantial carbon emissions "roughly on par with what Canada would be emitting as a society by mid-century," Rogers says. Hence, LSFMs and the new data fueling them may inform predictions of future climate change.

Augmented Reality

Although Brown hasn't put her field data into LFSMs, findings such as hers could help make better fire predictions. Knowing, for instance, that back-to-back burns would convert a black spruce forest to shrubby tundra, which is less flammable, might lead the models to predict a lower fire risk over time, she says.

Researchers are already plugging other field observations into LFSMs. Hansen led one such study in 2018, using iLand (8). Before his study, the model predicted which trees might regrow on a burned site using parameters including the distance seeds can be dispersed. But field data had shown that lodgepole pine and Douglas fir seedlings don't establish well in dry soils cleared of other vegetation by fire.

So Hansen updated iLand to account for the effects of soil moisture on seedling establishment. Then he ran an experiment with iLand, assessing how different climate change scenarios and a variety of preset fire recurrence intervals, from burns every 11 years to wildfire once in a century, as well as different distances to unburned seed sources, would influence forest recovery. As iLand whirred away on Hansen's computer screen, olive circles of lodgepole pines and blue circles of Douglas firs multiplied, until some stands were destroyed by a fire preset in the model. Each blaze wiped out all the trees covering a 1-hectare grid cell of the map. Then iLand simulated how the grid cell recovered over the next 30 years. Hansen compared the results with real field data on the density and species of seedlings and found that "tree regeneration patterns were much more realistic after we added the effects of soil moisture on whether seedlings survived," he says.

Land managers are dealing with unprecedented uncertainties about fire in the ecosystems they oversee. Ultimately, improved data should make the models more accurate—and better models should facilitate smarter fire management strategies.

Fire Control

To that end, Hansen led a 2019 study using the updated iLand model to compare the effects of different fire management scenarios, predicting the consequences for 40,000 hectares in Grand Teton National Park, WY, between 1989 and 2098 (9). Managers in Grand Teton have suppressed about 60% of lightning-caused wildfires since 1989, but recently they have considered letting more areas burn—in the case of low-risk natural wildfires caused by lightning—in hopes of consuming excess fuel. So Hansen tested two scenarios in iLand. In one, all lightning-caused wildfires are allowed to burn naturally. In the other, firefighters extinguish all wildfires when weather conditions allow, mimicking actual fire management today.

Surprisingly, iLand found little difference between the two scenarios. It projected a 1,700% increase in area burned between 2018 and 2098, compared with the period 1989 to 2017, regardless of management scenario. By 2098, the model also foresaw a 35% conversion of the landscape from forest to nonforest. Hansen suspects that outcomes of the two scenarios were similar because most of the landscape remained forested, even in the midst of a 35% loss. Hence, fuel loads stayed sufficiently high and forest patches sufficiently connected to spread fires.

The comparable outcomes suggest that managed wildfire use wouldn't improve on the suppression approach that's common to current fire management strategies. But managed wildfire use "could still have important benefits," Hansen notes. Although the intervention didn't reduce the number, size, or severity of fires in the simulations, it did create a patchier, more heterogeneous forest landscape, which might reduce the risk of other problems, such as bark beetle outbreaks spreading between forest patches, he says.

Another possible mitigation strategy is reseeding forests, such as black spruce, so that more frequent fires don't convert to grasslands for lack of tree seedlings. There are early attempts to do so—Seattle, WA-based DroneSeed, for example, deploys hovering drones to drop seeds over burned out forests and can propagate 40 acres in a day, according to the company's website. But widespread reseeding in boreal forests is unlikely in the near future, Brown says, because they are not considered economically important. And there's no guarantee that future environmental conditions will allow seeds to establish and forests to regenerate.

Even so, we need "all the tools we can have in our toolkit right now," Coop says. He adds one caveat: Replanting the same trees after a fire may not make sense in places where the future climate isn't projected to support those species. In New Mexico's Jemez Mountains, for example, the nonprofit Nature Conservancy is spearheading a project, along with multiple agency and tribal partners, to replant ponderosa pines after fires, he says, but at higher elevations—the likely location of future habitats as a result of climate change.

See Beyond the Tree

Although LFSMs are getting closer to simulating reality, they're still imperfect. iLand, for example, only sees forests for their trees. When it estimates that a forest will not recover, it leaves the scorched grid cells empty unless there is sufficient seed supply and appropriate climatic conditions for trees to reestablish. But in the real world, bare soil is rarely bare for long. The Yukon's reburned black spruce stands aren't just winking out; they're being replaced.

To bring models closer to reality, Hansen says, they should simulate the grasses and shrubs that establish when forests don't recover. Field studies show that fire aids some invasive grasses, which in turn can burn more frequently than trees. In places such as tropical savannahs, Hansen says, grasses burn often enough to keep forests from establishing. But whether forests will recover in areas converted to grassland in the western United States remains to be seen, he says. Capturing those fire–vegetation feedbacks would make LFSM models even more useful virtual simulators of the future real world.

Already, the charred spruce forests of Eagle Plains have few trees left. The tall swishing grasses, shrubs, and pink fireweed now rolling across that landscape will determine how susceptible it is to future fires—and perhaps just how far the flames will spread.

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