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THE NEW NORTH

Stoked by climate change, fire and insects are remaking the planet's vast boreal forest

By **Tim Appenzeller**

For 7 weeks last year, Yellowknife was besieged by smoke. In the vast evergreen forests encircling this small city in Canada's Northwest Territories, years of drought had set the scene for a historic fire year. Across the territories, 3.4 million hectares burned—an area equal to the state of Maryland, and seven times the annual average. The smoke darkened the sky, stung eyes, and filled Yellowknife residents with "a sense of panic," says Frank Lepine, who manages wildfire response for the Northwest Territories government.

When the snow fell and the fires died, Lepine's army of firefighters—about 1000 strong at one point—could stand down. But for scientists the work is just beginning. The fires, they say, were an extreme example of the forces transforming the boreal forest, a stronghold of spruce, pine, and other conifers that rings the top of the planet, spanning northern Canada, Alaska, Russia, and Scandinavia. With its millions of square kilometers of pristine timber, thick carpet of moss and needles, and organic-rich frozen soil, the boreal forest stores more carbon than any other land ecosystem. And more than any other forest, it is bearing the brunt of climate change, warming roughly twice as fast as the rest of the planet. The effects on its cold-adapted trees are already evident. "We are on the cusp of a transformation," says ecologist Michelle Mack of Northern Arizona University in Flagstaff.

The early signs can be seen from space,

where orbiting sensors that monitor photosynthesis show that much of the boreal belt is "browning": not literally turning brown but losing its vigor. They can be seen on the ground, in tree-ring studies that show trees are struggling to grow during the increasingly hot summers. They can be seen in insect outbreaks that are killing trees hundreds of kilometers farther north than they did 20 years ago. Most dramatically, the transformation can be seen in forest fires so fierce and voracious that they kick the forest into a new state, with a different mix of species and untold impacts on wildlife and climate.

"Fire is a catalyst for change," says Mike Flannigan, a fire specialist at the University of Alberta in Edmonton, Canada. Across the boreal, fires are burning as never before, favored by heat and drought that dry out the forest floor and spawn thunderstorms that bring lightning but little rain. In Canada, the total average area burned each year has more than doubled since the 1970s, Flannigan says—and that's in spite of more effective firefighting. In Alaska and Siberia, too, fire is on the rise. But it is a change in the nature of the fires, as much as their extent, that is transforming the forest.

The trees of the boreal, after all, are used to fire. The dominant species in Alaska and much of Canada, black spruce, maintains an aerial storehouse of seeds, locked in cones that form a distinctive tuft at the treetop. When a fire singes the cones and melts their resin, they spring open, releasing years of seeds all at once—an adaptation known as fire-mediated serotiny. Normally, this seed rain ensures that black spruce comes back strong after a fire, outcompeting other species. But the most severe fires can break this stranglehold and open the way to a new kind of forest.

When ecologist Jill Johnstone was a graduate student at the University of Alaska, Fairbanks, she set out to study how the boreal forest regenerates after fires of differing severities. A convenient laboratory was at hand: burned areas near Fairbanks left by recent fires. The severity of the fires had been low; they had spared much of the organic layer of moss and duff that carpets the floor of black spruce stands. Johnstone decided to simulate a more severe fire by taking a propane torch and burning off the organic layer to various depths, in some cases all the way to the bare, silty soil beneath. Then she sowed the seeds of spruce, aspen, and other trees, mimicking what happens after a natural fire.

Megafires such as this one in Canada's Northwest Territories last year are transforming the boreal forest.

Where the organic layer remained, she found that black spruce held the advantage. The charred duff "is a really bad seedbed" for most tree species, she says. "It's black, it dries out, and it heats up in the sun to 40°C. To regenerate trees you need to have a lot of seeds"—exactly what black spruce provides after a fire. But the spruce's advantage disappeared in plots where she burned off the organic layer. On the exposed soil, cooler and moister than the duff, aspen germinated in greater numbers.

Boreal fires increasingly resemble Johnstone's propane torch, searing the forest floor to bare soil. These days, "people talk about megafires," she says. "The fire weather is shifting." Fires are also recurring more frequently, in some cases sweeping across areas that burned as little as a decade before, consuming any organic material left on the forest floor. Today, Johnstone says, late-summer fires "burn and burn until the snow falls. They'll burn pretty much everything in their path—they'll blow right through old fire scars."

As her small-scale experiments suggested, black spruce is losing out. The clinching evidence came after Alaska experienced its biggest fire year in modern history in 2004. Some of the more than 700 fires just singed the forest floor, others blowtorched it away, giving Johnstone, Mack, and their colleagues a chance to compare how the forest recovered over large areas. Four years after the fires, they surveyed 90 burned sites and found that whereas those with an intact organic layer were thick with baby black spruce, sites where the fires had left bare soil were typically covered with seedlings of trembling aspen and paper birch. At those sites, Johnstone, Mack, and their colleagues wrote in 2010, the "legacy lock" of black spruce was broken.

After fires, clusters of cones in the tops of black spruce release a rain of seeds that ensures a new generation of spruce. But the most severe fires allow other species to take over.

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To a satellite looking down on the forest, aspen and birch appear brighter than black spruce, says Scott Goetz, a remote-sensing expert at the Woods Hole Research Center in Falmouth, Massachusetts. By matching up a record of Alaska's most severe fires over the past 50 years with satellite measurements of forest brightness, he and colleagues including Mack confirmed the pattern seen on the ground: The most severe fires led to the most extensive regrowth of deciduous trees. Other researchers predict that deciduous stands, which accounted for less than half of interior Alaska's forests in 2001, will expand to cover two-thirds of the forested area by 2020.

Once established, researchers say, the broad-leaved trees are unlikely to be dislodged, as they grow faster and are less prone to burning than the conifers they replaced. For black spruce, the shift spells the end of a long reign, Johnstone says. "Black spruce have been pretty stable on the landscape for about 5000 years—we can tell from pollen records."

Not every year brings a forest-transforming megafire. But warming temperatures are applying their own, steadier pressure to the forest. Again, the effects are apparent from space, in data from sensors that monitor specific wavelengths of light absorbed by chlorophyll. The resulting false-color maps show much of the boreal belt in green, indicating vigorous photosynthesis. But at its heart, especially in North America, are regions where photosynthesis—the vital function of a forest—has slowed over the past 30 years. They are depicted as patches of brown.

When Goetz and his colleagues reported the browning in 2005, he says, "it certainly got people's attention." Modelers had expected the warming of the north, together with a fertilizing effect from rising carbon dioxide, to trigger a surge of forest growth. Instead, wide swaths—roughly a quarter of Alaska's forest, Goetz estimates—are languishing.

The browning isn't always obvious at ground level, but land-based measurements corroborate the remote sensing. Collaborators of Goetz's took core samples from black and white spruce, another common tree in the boreal, across much of Alaska, then analyzed tree rings to track the trees' growth history. In nearly every sample from the interior of the state, they reported in 2011, the rings had narrowed over the past 30 years, and the density of the annual increments of wood had risen. Those are signs that the increasingly hot summers are causing the trees to run short of water. To stem water loss, they are narrowing tiny pores, or stomata, on their needles—choking off their intake of carbon dioxide and slowing photosynthesis.

If the trend continues, the trees will begin to die, says Glenn Juday, a forestry expert at the University of Alaska, Fairbanks, who collaborated with Goetz on the 2011 study. In a new tree-ring study, Juday and his colleagues studied growth trends in white spruce at sites across Alaska. They found that trees in the interior of the state, where summers are hotter and drier than near the coast, are struggling to keep pace with climate warming. (Annual average temperatures at Fairbanks are up 1.5°C over the past 50 years.) Conditions are now nearing the trees' physiological limits, they fear. "Coming generations won't see the same large, old conifers," Juday predicts.

Besides stressing trees directly, warming is favoring their enemies: the insect pests that are exploding across the boreal forest. Warming is enabling them to expand their ranges by accelerating their life cycles, helping them survive the winter, and weakening host trees. One of the most dramatic cases involves the mountain pine beetle. Until the late 1990s, the scourge was confined to lodgepole pine in British Columbia, west of the Canadian Rockies. Scientists had hoped that two barriers would restrain its spread: the Rockies and a vegetation boundary just to the east of the mountains, where the beetle's favored lodgepole pine gives way to a related species, jack pine.

Those hopes were dashed, says insect specialist Barry Cooke of the Canadian Forest Service in Edmonton. In the mid-2000s, the beetle staged "a mass exodus," spilling eastward into Alberta and attacking jack pine. So far its range has extended 300 kilometers to the east and more than 1000 kilometers to the north, Cooke estimates. "The mountain pine beetle is poised to go all the way to Newfoundland" on Canada's eastern seaboard, he says.

The beetle joins a host of other boreal pests on the march: the spruce beetle, western spruce budworm, Douglas-fir tussock moth, hemlock looper, and willow leaf blotch miner, to name a few. And like severe fires, Cooke says the worst insect outbreaks may drive long-lasting ecological change, as the denuded forests regrow in a different form, better adapted to the new normal. "We will see irreversible changes. Whereas insects used to play a temporary role, they will become agents of permanent change."

Researchers have varying visions of what the future boreal forest will look like. "I think there will be shrublands, even grass," Flannigan says. "My gut instinct is that the forest may be gone in some places."

"I think we're going to see some interesting changes regionally," says Carissa Brown, a former student of Johnstone's who is now at Memorial University of Newfoundland in St. John's. But she's cautiously optimistic: "The boreal forest is a very resilient system."

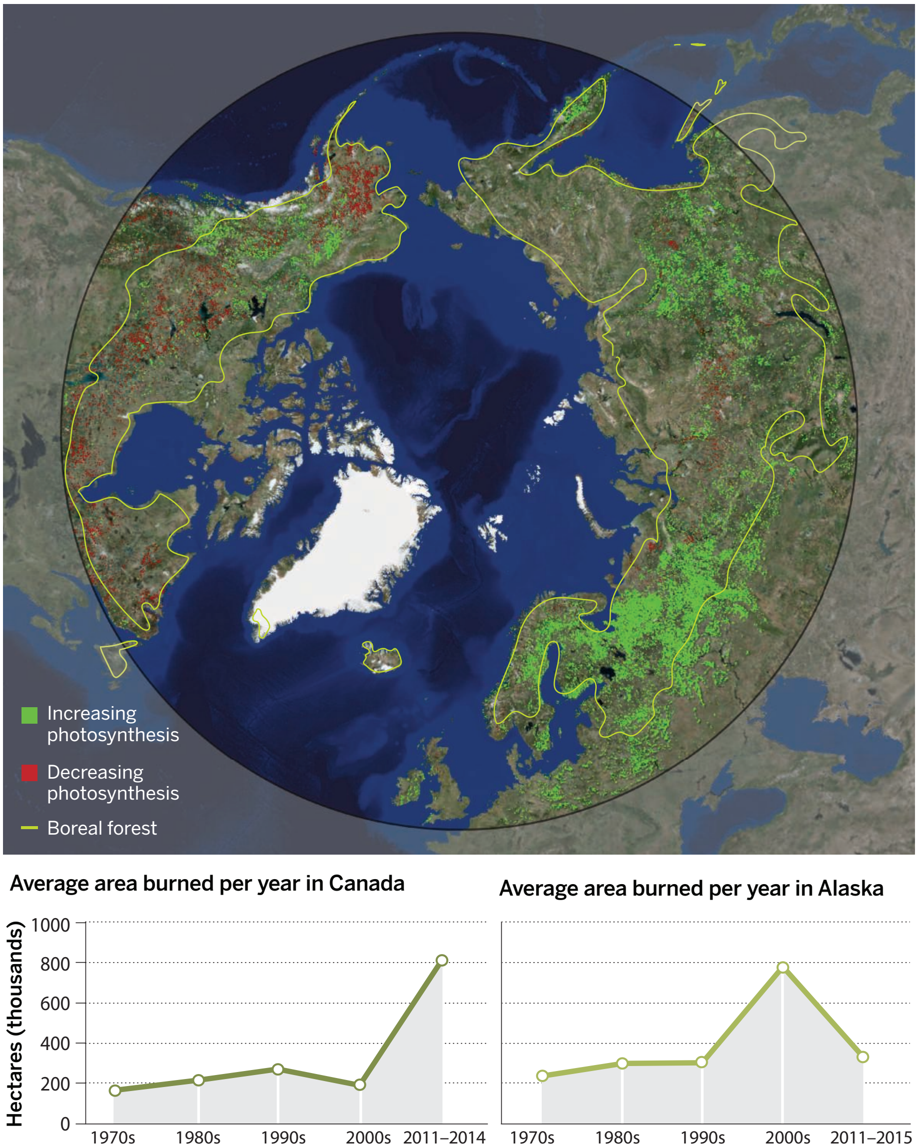
Juday suggests it may respond by migrating. Although his recent study showed that trees in the center of Alaska are suffering, it revealed a surge of growth near the Bering Sea coast, where summers are cooler and wetter and the forest gives way to tundra. The productive heart of the forest is shifting, Juday says. "An early stage of biome shift is underway."

Whatever the new shape of the forest, the change will ripple through wildlife communities. Caribou, for instance, like evergreen black spruce stands, which are carpeted with lichen, an important forage. But in stands of deciduous aspen and birch, the lichen never gain a foothold among the fallen leaves. "That takes from the caribou their source of winter forage," Brown says. Moose, on the other hand, are fond of aspen shoots and may thrive as the broadleaf forest expands.

The transformation will also affect climate, for better and worse. Fires, for example, turn wood and needles into climate-warming carbon dioxide—a positive feedback. But Mack, who has studied carbon flows in the changing forest, says that forest regrowth ultimately takes up the lost carbon—especially when aspen, which grows fast and quickly locks away carbon in wood, takes over. The spread of aspen could even restrain climate change through a pair of negative feedbacks: The aspen canopy reflects more sunlight than spruce, and broadleaf forests are less flammable.

Feeling the heat

Satellite data show that photosynthesis has declined (brown) over the last 30 years in much of North America's boreal forest belt while increasing (light green) in parts of Russia and Scandinavia, where forests have responded differently to warming temperatures. Warming is also driving an increase in massive forest fires, in both Alaska and Canada (bottom).



CREDITS: (BOREAL) BRENDAN ROGERS, WOODS HOLE RESEARCH CENTER; DATA SOURCE: (ALASKA FIRES) ALASKA INTERAGENCY COORDINATION CENTER; (CANADA FIRES) MIKE FLANNIGAN, UNIVERSITY OF ALBERTA

Bad news, however, may be unfolding below the forest floor. Underlying much of the boreal forest is permafrost, deep-frozen soil filled with thousands of years of organic matter—a massive reserve of carbon. The duff layer beneath a spruce forest, up to a meter thick, insulates the permafrost from summer warmth. But when a fire burns off the duff, the permafrost can start to thaw and release carbon dioxide or methane, another potent warming gas. After a severe fire in the Yukon, Brown recalls, "we even had a hillside fall away" as the frozen soil softened. "You could actually smell all that carbon being released."

Nature is providing plenty of opportunities for further study. The scars of last year's fires in the Northwest Territories are now a field site for Johnstone, Mack, and other researchers. And this year's fire season promises a generous new crop of natural experiments. In the Northwest Territories, the burning season it got an early start thanks to a phenomenon that used to be rare: a dozen "holdover fires" that started last year and then smoldered beneath snowbanks through the long winter. With the spring thaw, the flames rekindled, and the transformation of the boreal forest began anew. ■