Science Update

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INSIDE

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Warming in the Cold North

Unlocked doors in Utqiaġvik

The town of Utqiaġvik, Alaska, has an unspoken rule: always leave the outer door to your house unlocked. Formerly known as Barrow, Utqiaġvik (pronounced oot-ghar-vik) is the northernmost community in the United States, located 300 miles north of the Arctic Circle on the Arctic Ocean. It was renamed in 2016 to restore the town's traditional Inupiaq name.

Houses are built on pilings because the ground is permafrost—permanently frozen. If a building sits directly on the ground, its heat thaws the icy soil causing the structure to sink into soft mud. In the Alaskan Arctic, permafrost can be as cold as 14 °F (-10 °C) and up to 2,000 feet thick.

The Arctic tundra is one of the Earth's coldest and harshest biomes. Ecologist Janet Prevéy experienced this in person in 2015. "I was there in August and it was freezing. There are no trees for miles," she said. "It's a stark landscape with these really hardy little plants that don't grow more than three inches off the ground."

Prevéy was collecting data on those plants, alongside two field technicians. They took advantage of the almost perpetual daylight and worked until 7:00 or 8:00 at night, kneeling for hours over tiny plants. They would pull nitrile gloves over their regular winter gloves to try to keep their hands dry because the cold so quickly numbed all feeling from their fingers.

Greg Hayward

Boreal forests, like this one near Lake Louise, Alaska, are one of the planet's biomes that are expected to change the most rapidly with future climate change.

Key Points

- The Arctic and boreal regions are warming more than twice as rapidly as the rest of the world. Alaska's interior boreal forests are sensitive to changes in temperature and moisture, leading to increased risk of fire and more favorable conditions for several pathogens and insects.
- With projections of continued warming, Alaska's boreal forest will undergo significant functional and structural changes within the next few decades that have been unprecedented in the past 6,000 years.
- Tundra plants are showing greater temperature sensitivity in the timing of greening and flowering in colder, higher latitude sites than at warmer, lower latitude sites. The timing of plants' flowering and fruiting has implications for insects and wildlife species in Alaska.
- The Chugach National Forest, in collaboration with Pacific Northwest Research Station scientists, completed a vulnerability assessment that helps land managers understand the potential consequences of climate change for key natural resources in the region.

Janet Prevéy

"We would wear as many clothes as we possibly could. The tundra there is completely flat and it's right up against the ocean, so there was a strong wind all day long. The ground was quite wet so we wore big heavy boots. It felt like you were walking across a big wet sponge," Prevéy said.

Robert Barrett

Ecologist Janet Prevéy stands next to a study plot in the Alaska Arctic. These plots were established 28 years ago as part of the International Tundra Experiment. Prevéy's syntheses of long-term data from these sites is helping to show the rapid changes occurring in tundra ecosystems.

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Pacific Northwest Research Station
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P.O. Box 3890
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(503) 808-2100

Cynthia L. Miner, Communications and Applications Director, cynthia.miner@usda.gov

Rachel White, Writer and Managing Editor, rachel.e.white@usda.gov

Jason Blake, Layout, jason.p.blake@usda.gov

Send change of address information to SM.FS.pnw_pnwpubs@usda.gov

◄ *Increasing summer temperatures are shifting the flowering times of plants in high-latitude places such as this tundra landscape.*

Robert Barrett

Field technician Robert Barrett collects data on hardy Arctic plants while trying to keep his fingers warm at the International Tundra Experiment study site near Utqiaġvik.

Prevéy studies plant phenology, which refers to the timing of biological cycles, such as when plants leaf out or flower. Climate change is influencing plant phenology, and the far North is a logical place to study this response because high-latitude regions are warming faster than other parts of the world. Her approach involves comparing phenology observations from different species and sites over many years. It allows her to unravel how temperature change affects the timing of ecologically critical events in the life cycles of plants in these cold latitudes. The changes Prevéy is documenting have ripple effects that spread beyond the Arctic throughout Alaska and the subarctic regions for many other inhabitants, including Alaska Native villagers, caribou, migratory birds, and even grizzly bears.

Doing fieldwork in the Arctic tundra requires certain safety precautions. As they crouched to gather data, Prevéy and the field technicians kept one eye out for polar bears. "Polar bears are one of the species of bears that will actually go after people to eat them," she said. "So I was looking up every five minutes. I never did see one, but it was exciting to know people had seen them in the past." This is the reason the locals in Utqiaġvik leave their doors unlocked. If anyone out and about encounters a polar bear, they can run to the nearest house and quickly get inside.

Robert Barrett

Data gathered from plots like this one in the International Tundra Experiment study site near Utqiaġvik, Alaska, are helping scientists address important questions about temperature sensitivity in plants in cold, high-latitude landscapes.

"The Boreal Forest is Incredibly Dynamic"

Teresa Hollingsworth, a research ecologist with the Pacific Northwest Research Station, also studies plants, in Fairbanks, Alaska. During her undergraduate studies at the University of Colorado, she took a post as a teaching assistant for a field ecology course in the Canadian Arctic. She fell so in love with the North that several years later when seeking a Ph.D. project, she tried to find a position that would take her back there. Instead, she heard of an opening to study the boreal forest in interior Alaska, which is south of the Arctic and a totally different ecosystem.

"I thought I would be here for four years and move on," she said. "But I got really excited about boreal forests, which I never expected. The boreal forest is incredibly dynamic. That is what I love about it. Change is such a part of the system. Little changes, big changes—disturbances happen here in a way that you don't have in the Arctic. The Arctic is a slow-changing system, without big disturbances, at least historically."

Teresa Hollingsworth

Research ecologist Teresa Hollingsworth studies boreal forests and is the Forest Service lead for the Bonanza Creek Long-Term Ecological Research site.

Change has visibly shaped the boreal forest. "I remember something a pilot said when I was working on my Ph.D.," Hollingsworth recalled. "We were flying over the boreal forest and he said 'Look down. There's not a place on that landscape that hasn't been affected by either fire or flooding.' I looked out and was like, wow he's right."

The interior Alaska boreal forest is vast, accounting for one-fifth of the forest land in the entire United States. Also known as the taiga, or snow forest, it is a land of extremes. Harsh conditions include long, frigid winters, short, dry summers, and frequent fires. Plant diversity is low. The Alaska boreal forest is composed primarily of two coniferous tree species, white and black spruce. These trees, together with two deciduous trees, aspen and birch, form a nearly continuous blanket across the uplands of Alaska between the Brooks Range in the north and the Alaska Range in the south.

When she was in graduate school, Hollingsworth wrote about boreal forests in a poem:

a wrinkle of light
watching
the clouds and mountains and trees and river
disappear into
the pink and blue and whiteness and darkness.

JLS Photography

Boreal forests, which maintain a fragile balance in a land of extremes, are already experiencing extensive disturbance, such as permafrost thaw, insect outbreaks, and fire.

This serene image invokes a primeval landscape. The remoteness and sheer scale of this forest almost make it seem invulnerable. But today's boreal forest represents a fragile balance. The trees and plants are very sensitive to changes in environmental conditions and closely dependent on temperature and the "permanence" of permafrost.

Hollingsworth and other scientists are alert to these implications. The arctic and boreal regions are warming more than twice as rapidly as the rest of the world. Some of the largest annual air temperature increases are occurring in Alaska's interior boreal forests. Change may be part of the system, but change of this magnitude could have disastrous consequences for the wildlife and people who rely on boreal forests for food and livelihoods.

"What's unique about the boreal forest is it's such a big landscape," Hollingsworth said. "In 2004 and 2005, the combined area burned by wildfire was the size of Colorado. Our biggest fire in 2004 was 500,000 hectares [more than 1 million acres]. So huge, huge areas are just—bam—affected at once. Same with permafrost. Permafrost is soil that essentially stays frozen, so below zero degrees Celsius. What's fascinating about permafrost in the boreal forest, unlike in the Arctic, is even before we started to see these rapid shifts in temperature, we were already at the cusp of thawing, at -0.5 °C. In the Arctic, where the average soil temperature is -10 °C, it would take a 10 °C shift for it to thaw. But here in the boreal forest, you only have to have a shift of 0.5 °C to have major thawing of permafrost, which has cascading effects."

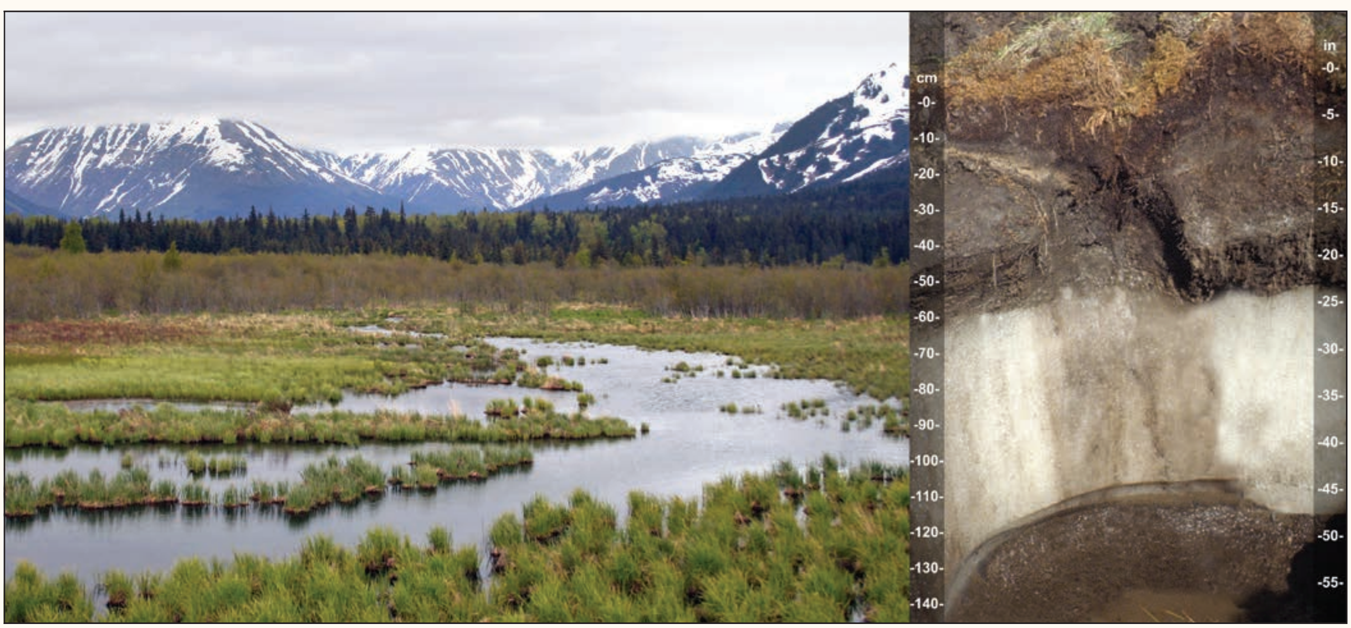
Unprecedented in 6,000 Years

Grasping what climate change is doing to this expansive forest requires a long research horizon that can make sense of ecosystem variations over many years. Fortunately, a program exists that is designed specifically to gain this broad perspective of boreal forests. The Bonanza Creek Long-Term Ecological Research program, centered near Fairbanks, Alaska, focuses on how climate change and disturbances such as wildfire affect the Alaska boreal forest, and what the consequences are for the sustainability of subsistence in Alaska communities.

Jointly managed by the Forest Service Pacific Northwest Research Station and University of Alaska Fairbanks, it is part of the larger Long-Term Ecological Research (LTER) network comprising 2,000 scientists and graduate students and 28 research sites across the continent that represent a diversity of ecosystems. Hollingsworth is the Forest Service lead for Bonanza Creek's LTER program.

"The Bonanza Creek LTER program is critical to Forest Service research because it's the only Forest Service outpost in the boreal forest, which is the biggest forest in the world," said Hollingsworth.

Research at Bonanza Creek has helped paint a picture of a boreal ecosystem that maintained a stable balance of disturbance dynamics for millennia. Hollingsworth co-authored a study published in *Canadian Journal of Forestry Research* that explored the remarkable capacity of Alaska's boreal forest to absorb and bounce back from climatic fluctuations.



John A. Kelley

Permafrost underlies more than 80 percent of Alaska's land. As this frozen ground thaws under climate change, it is reshaping the landscape as well as releasing carbon gases that fuel global warming.

Geoff Liesik

The aftermath of a severe fire in boreal forest. Severe fire is becoming more common in boreal forests, disrupting conditions that have sustained black spruce dominance for thousands of years.

"Our system has been incredibly resilient over the past 6,000 years to climatic perturbations," she said. As her study explains, the landscape evolved into its current mosaic about 5,000 to 7,000 years ago when black spruce assumed its role as dominant species.

"Historically, once black spruce came into our landscape, fire has been a driving factor in vegetation dynamics. There is a balance with these trees adapted to a self-perpetuating cycle of fire, black spruce, fire, black spruce. These forests have been living in that world for 6,000 years," Hollingsworth said.

However, the warming trend that has ramped up since the 1950s is unlike any climatic perturbation these forests have ever experienced. Hollingsworth and her co-authors suggest that with projections of continued warming, Alaska's boreal forest will undergo significant functional and structural changes within the next few decades that have been unprecedented in the past 6,000 years. "We conclude that the Alaskan boreal system remains quite resilient but is undergoing changes in ecosystem and landscape structure, feedbacks, and interactions that,

JLS Photography

A red sunrise glows through the smoke from wildfires in July 2019, one of Alaska's biggest fire seasons in decades. As of August, 2.5 million acres of Alaskan forest—an area more than three times the size of Rhode Island—have burned.

with continued warming, will likely cause reorganization or potential transformation to a fundamentally different system," they wrote.

What this means for boreal forests is still unclear. Have these systems already reached a tipping point, leading to substantial changes in landscape cover, or will they eventually become resilient again? Hollingsworth wonders about this as she continues to study this dynamic landscape. "Even small changes in this disturbance regime can create really big changes in vegetation," she said. "We have very low vascular plant diversity here because it's so cold. So any time you have an insect outbreak or a fire, it's a big deal. In a different forest where you have many plant species, a change in the disturbance regime might cause some ebbs and flows. But when you have just six tree species, they cover a large landscape. If a fire rips through that is different than what the landscape has experienced in the past, it's ripe for invasion and even shifts in spe-cies dominance."

The boreal forest is one of the Earth's biomes expected to change most rapidly with future climate change. The research Hollingsworth helps direct at Bonanza Creek explores what this change will look like. "We want to be able to pinpoint what are the big, most noticeable changes. Based on our observations and also current research, we came up with three areas: fire, permafrost, and insect and pathogen outbreaks."

Disturbances such as permafrost thaw, fire, and insect outbreaks are already more extensive than at any time in the historical record. For example, the annual area burned in Alaska has increased dramatically in the past 60 years, and notably in the past 15 years. Warmer and drier summers allow fires to continue burning in late summer. The area burned during late season fires in the 2000s was three times higher than in any previous decade since 1950. Of all the fires that have burned in Alaska since 1950, 85 percent have been in the interior boreal forests.

Each of these changes has consequences for wildlife species, including the billions of migratory birds that breed in the boreal forest across its extent in North America, as well as the local communities of people with a strong tradition of living off the land. And the consequences don't stop at the edge of the forest.

JLS Photography

Scientists at Bonanza Creek predict that climate change will affect boreal forests. One change may include increases in pathogen outbreaks. The orange dust on this branch is spruce broom rust, a pathogen that can make a tree more vulnerable to other disturbances.

Lisa Hupp

During spring migration, up to 3 billion birds, such as this Savannah Sparrow, migrate north up to their breeding grounds in the boreal forest each year.

Ripples Far and Wide

From Plant Timing to Bears

Growing up, Janet Prevéy became very familiar with different types of forest trees and plants. "My parents both worked for the Forest Service. I was lucky in that I got to grow up in a lot of beautiful places and live in the woods as a kid in ranger stations," she said. She lived in California, Arizona, New Mexico, and Florida. She got her Ph.D. in ecology at the University of Colorado in 2014. From 2016 to 2019, she worked for the U.S. Forest Service Pacific Northwest Research Station as a post-doctorate plant ecologist, before taking a position as a research ecologist with the U.S. Geological Survey in Colorado.

Prevéy's field work in Utqiaġvik (oot-ghar-vik) was part of a larger study she led that spanned a climatic gradient including sub-Arctic, sub-Arctic alpine, and Arctic tundra. Eleven of her 18 field sites were established as part of the collaborative and ambitious International Tundra Experiment, established in the early 1990s. Most of her field work was in the Swiss Alps. Her study, published in *Global Change Biology*, is one of the first ever to examine whether the temperature sensitivity of plant cycles—leafing out, blooming, and going to seed—differs among tundra sites experiencing different climatic conditions. The reason this question is important is that cold environments have short growing seasons, so plants are under strong selective pressure to start growing and flowering just as soon as temperatures allow in the spring. Thus, plants in these environments respond to small changes in temperatures during the growing season. If climate change is affecting northern latitudes more rapidly than the rest of the world, what is it doing to these plants whose survival depends on their response to temperature?

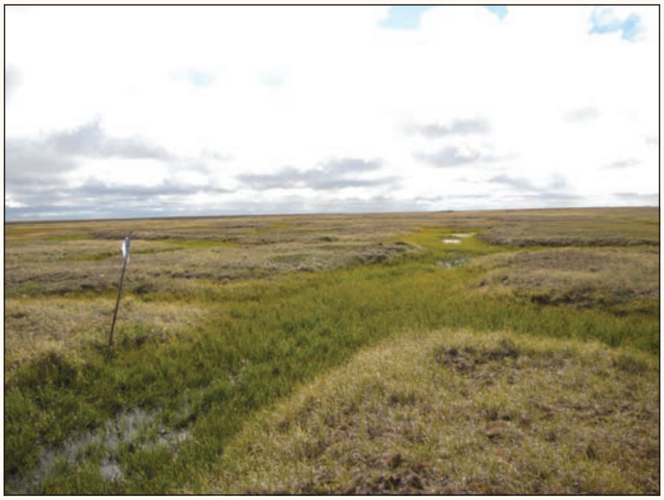
In addition to collecting her own data, Prevéy made use of the largest collection of high-latitude field data on plant phenology to date, collected by hundreds of scientists and field assistants. She analyzed 20 years of data on the dates when leaves and flowers appear and die for 47 species of tundra plants at different sites and elevations.

She and her team found evidence for greater temperature sensitivity in the timing of greening and flowering of tundra plants in colder, higher latitude sites than at warmer, lower latitude sites. They also found that the temperature increase in spring and early summer over the past 50 years has been greater in colder, higher latitude sites than in warmer, lower latitude sites. "Specifically, our results suggest that increased summer temperatures will shift the flowering times of plants from colder, higher latitude sites earlier to overlap more with those of populations from warmer sites," Prevéy explained.

These are among the first results to document differing responses of tundra plants across a climatic gradient. Interestingly, Prevéy's results also suggest that as summer temperatures create more overlap between flowering times of plants from colder and warmer sites, gene flow between populations could increase, with as yet unknown consequences.

Prevéy contributed to an even larger synthesis of plant traits over time, recently published in *Nature*, which found a "ubiquitous" increase in plant heights. These studies add to the growing evidence that rapid changes are already occurring in tundra ecosystems.

Robert Barrett



The Arctic tundra is a cold and harsh landscape, with a very short growing season. The survival of plants growing here depends on their ability to respond to temperature changes.

Robert Barrett

*A dwarf fireweed (*Chamaenerion latifolium*) growing in the Arctic. For plants like this one, the timing of flowering and other life events is being altered by climate change.*

Assessing the temperature sensitivity of Arctic plants provides valuable scientific understanding of the effects of climate change in a rapidly warming ecosystem. But it is also important from a social and cultural perspective, as there are alarming implications for people and wildlife who rely on food resources like berries. As Prevéy explained, “The timing of when food resources like berries are available on the landscape is changing a lot with climate change.”

Research confirms that the seasonal timetable shaping these ecosystems has begun going haywire for grizzly bears in Alaska. Normally, bears would feed on salmon at the peak of the spawning run, then shift to red elderberries later in the season as the berries ripen. But in warm years, the berries are now ripening at the same time as salmon season, forcing the bears to choose between food sources. These changes likely have nutritional costs for bears and are already disrupting food webs, causing ripples throughout the entire ecosystem.

Robert Barrett

Many Arctic and tundra wildlife species have adapted to the seasonal timetable of plant life cycles, which are being disrupted by climate change. There are also alarming implications for people who rely on food resources such as berries.

National Park Service Climate Response

In northern Alaska, an exceptionally warm summer in 2004 triggered this 300-m-long slump associated with thawing permafrost.

Global Implications

Permafrost stores massive amounts of carbon. When it thaws, in addition to causing local erosion, landslides, and changes in plant species composition, it releases the stored carbon as methane and carbon dioxide. Once they get back into the atmosphere, these gases trap heat, accelerating climate warming in a feedback cycle that further accelerates warming.

"A huge amount of the world's soil carbon is locked up in the boreal forest," Hollingsworth said. "You get permafrost thaw, you get fire, and interactions between those two, and all of a sudden a quarter of the world's soil carbon is available to be burned off or decomposed and released into our atmosphere. And that's a really huge deal with major global implications emanating from changes in our fire cycle."

One of the guiding research questions at the Bonanza Creek Long-Term Ecological Research program focuses on how the boreal biome is responding to climate change and what the global impacts might be. Hollingsworth and the other scientists there have made it a goal to address this question in a way that is directly relevant to the information needs of land managers and policy makers.

Following this principle, scientists produced a review outlining the sources and sinks of carbon in boreal ecosystems of interior Alaska. They pointed out that fire is the dominant disturbance in the boreal forest, and provides the fastest means of altering whether carbon is being released or stored. The report helps land managers in interior Alaska understand how a warming future climate, an increase in fire severity and extent, and the potential degradation of permafrost could lead to major landscape and carbon cycle changes over the next 20 to 50 years. In the near term, the upland areas of boreal ecosystems are expected to see increased fire frequency and an overall reduction in black and white spruce forests, which will likely lead to increases in carbon dioxide emissions.

This suggests that the way fires are managed could make a big difference in preserving carbon in surface soils and maintaining permafrost stability. Actively managing fires and encouraging low- to medium-severity fires could help reduce the loss of deep soil carbon during and immediately following larger, more severe fires.

Neal Herbert

Scientists at the Pacific Northwest Research Station studied potential outcomes for different forest habitats for the next five decades. This work contributed to a vulnerability assessment that will help forest planners address resources valued by communities in the region, such as snow and ice, coasts and seascapes, salmon, vegetation, wildlife, and infrastructure.

Assessing Vulnerability

Forest Planning in the 21st Century

Trees are also a critical part of the carbon cycle. They pull carbon dioxide out of the air and store it, using the sun's energy to convert the carbon into trunks, branches, roots and leaves via photosynthesis. Each year, forests around the world are a net carbon storehouse, or carbon sink, removing 1 to 2 billion tons from the atmosphere. This puts forests in a unique position: their health is vulnerable to climate change, while at the same time they contribute to regulating climate change.

The decisions made by forest managers therefore carry significant weight, with the potential to help reduce the negative effects of climate change on forests, and protect the capacity of forests to mitigate climate change.

Incorporating climate change impacts and adaptation into forest management became a national priority in 2012 when the regulatory guidance for the management of all national forests, known as the Forest Planning Rule, was being overhauled for the first time since 1982. Each national forest or grassland has a land management plan, or "forest plan," that guides decisions. Forest plans are revised every 10 to 15 years, and must follow the requirements laid out in the National Forest Management Act of 1976 and associated regulations in the forest planning rule. The revised 2012 planning rule, for the first time, wove the issue of climate change into guidelines for land management. National forests and grasslands are now required to consider climate change impacts, including vulnerability and adaptation, in their forest plans.

To operationalize climate change policy, the Forest Service also created a climate change performance scorecard, to be completed annually by each national forest. The scorecard is a checklist of 10 elements designed to help forest managers assess progress in agency efforts to respond to climate change.

Furthermore, all 154 national forests and 20 grasslands are required to revise their land management plans, beginning with eight "early adopter" forests. The Chugach National Forest in Alaska was one of these early adopters implementing the 2012 planning rule as they revise their land management plan.

South-central Alaska's Chugach National Forest is the nation's most northerly and westerly national forest. The size of New Hampshire, it spans nearly 7 million acres of shorelines, glaciers, forests and rivers, much of which is untouched by roads or trails. The Copper River Delta—the largest contiguous wetlands complex on North America's Pacific Coast—is on the Chugach and considered one of the most essential shorebird habitats in the world. More bald eagles live within the Chugach than in the entire lower 48 states combined. Conditions are less extreme here than in the boreal forest farther north. The Chugach landscapes primarily support temperate rain forest tree species (western hemlock, Sitka spruce, and mountain hemlock), but a small portion of its western edge, on the Kenai Peninsula, is boreal forest.

Pat Hayward

Greg Hayward, regional wildlife ecologist for the Forest Service's Alaska Region led a major effort to assess consequences of climate change on the Chugach National Forest.

"The Chugach had already begun considering climate change for a number of years, even before the new planning rule," said Greg Hayward, regional wildlife ecologist for the Forest Service's Alaska Region.

Hayward has a Ph.D. in wildlife ecology and years of experience studying boreal owls, grizzly bears, trout, marine birds, red-backed voles, and many other wildlife species (including tigers in Siberia). In his current position, which he has held since 2010, he serves as a science advisor to land managers, building a bridge between the latest research developments and the practitioners who make management decisions. "The role that I play is science delivery. I have done scientific research, but I get a lot of fulfillment out of doing this rather than developing new knowledge," he said. "My job is to inform policy and practice with science."

He recently led a major effort, with the help of several Pacific Northwest Research Station scientists and more than 20 other collaborators, to assess some of the key biophysical and economic consequences of a changing climate over the next five decades on the Chugach National Forest.

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Remote Sensing the Remote Forest

"Interior Alaska's forests were really the last frontier in terms of forest inventory," said Pacific Northwest Research Sation research forester Hans Andersen. Composed of about 110 million acres, with its thawing permafrost and changes in vegetation, fire, carbon, and water cycles, this dynamic forest landscape offers a window into the effects of climate change. But until recently, it remained a blank slate in terms of comprehensive monitoring data.

The Forest Service's Forest Inventory and Analysis (FIA) program is charged with completing annual forest inventories across all land ownerships in all 50 states. However, vast interior Alaska, which includes the only example of boreal forest in the country, was too remote and logistically challenging for field crews to collect data from. This gap in the nation's forest inventory represented a lot of missing information about forest change, particularly given that Alaska's Arctic and boreal ecosystems are experiencing warming temperatures at twice the rate of the rest of the world.

Almost all of Alaska's interior forest is roadless. Over the years, Andersen had watched proposals to extend FIA's inventory into this remote frontier get rejected, often because of the expense involved in sending field crews to every plot by helicopter. This changed in 2013 when he learned about a new National Aeronautics and Space Administration (NASA) project.

"It was a fortuitous occasion," said Andersen. "Through interactions with some scientists at NASA, I heard that they were in the process of developing a new airborne remote sensing system involving complementary technologies—LiDAR, hyperspectral, and thermal sensors. I thought this might be a great way to develop a collaboration with NASA and finally make it possible to implement the interior Alaska inventory by augmenting on-the-ground data collection with remotely sensed data."

Remote sensing can acquire staggering amounts of information about forest structure and terrain by scanning via satellite or aircraft; it offers a high-tech opportunity to view forest changes that would take a lifetime to measure on the ground.

The collaboration Andersen ignited, which now also includes the State of Alaska Department of Natural Resources, has been a resounding success. In 2016, full implementation of the inventory in interior Alaska began. Field crews started collecting data at 4,800 new field plots, while flight crew gather remotely sensed data through NASA's Goddard's LiDAR, Hyperspectral, and Thermal (G-LiHT) airborne imager.

Like any good scientist, Andersen is excited about the wealth of information being gathered by the G-LiHT sensors. "The different sensors provide complementary information," he said. "The LiDAR part is a laser pulse that goes down through the tree canopy and gives you a really dense 3-dimensional point cloud that represents the structure of the forest canopy. The thermal sensor measures surface temperatures and can be used to detect heat or moisture stress."

"The hyperspectral sensor gives you an image from the top surface of the canopy and includes 114 bands of spectral reflectance information," Andersen explained. For comparison, the human eye sees colors in three bands. Hyperspectral sensing divides images into spectra beyond the visible. "It lets us look at basic things like forest type, or species composition. There's a lot of information we can get from the spectral signature. You can extract indices that are sensitive to particular biochemical features of the tree canopy, like pigment concentrations or chlorophyll. There is a large number of spectral indices that are related to forest health and productivity and condition that you can extract from that spectrum."

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Example of Goddard's LiDAR, Hyperspectral, and Thermal imaging system airborne remote sensing data collected in interior Alaska. Remote sensing technology has revolutionized the collection of forest structure data.

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Chris Ferguson

Most of Alaska's interior forest is roadless. Field crews collecting data in these remote places have to be flown in by helicopter.

All of these new data will help provide baseline informa-tion on the extent, condition, and trends of interior Alaska forests. The remote sensing data also makes it possible to have a sparser grid of field plots, which cuts down on the number of crews that have to collect data by hand. This is major consideration, as virtually all the field plots have to be accessed by helicopter.

"Using state-of-the-art remote sensing is a way for us to fill in the gaps, and augment and provide some rich airborne data to get us up to the level of precision for the estimates we needed," said Andersen.

Innovative statistical analysis allows Andersen to integrate the different sources of data. "I spend a lot time working with NASA and other collaborators to figure out how we can use the remote-sensing data most effectively to support the inventory."

As his colleague Teresa Hollingsworth's research has indicated, the boreal forest is expected to undergo changes within the next few decades that are unprecedented in the past 6,000 years. Thanks to Andersen, his collaborators at NASA and the State of Alaska, and the intrepid field crews, there is now a system in place to monitor the vital signs of these unique forests, and the rest of the world will now be able to follow along as these changes unfold.

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Snow and ice, coasts and seascapes, salmon, vegetation, wildlife, and infrastructure

Each national forest now works toward checking off the boxes on its climate change scorecard. "One of the elements on the scorecard is a vulnerability assessment," said Hayward. "This came out of the recognition that for each forest, one of the very first steps in getting your arms around management in relation to climate change is assessing vulnerability."

Hayward brought together a team of 33 federal resource managers, scientists, and economists, as well as professionals from the private sector, to discuss the potential consequences of climate change and to find out what matters most to these local stakeholders. "We got together a broad array of people and we started asking questions about what we need to know to effectively write a forest plan revision and manage the Chugach. During a two-day workshop the group came up with the priorities. It was a collaborative process." The group narrowed their focus to a limited range of topics that would form the chapters of their final report: snow and ice, coasts and seascapes, salmon, vegetation, wildlife, and infrastructure.

Hayward enlisted the help of Pacific Northwest Research Station ecologist Teresa Hollingsworth and was grateful he did. "Of all the portions of the assessment, the piece on vegetation we were finding most complex," he said. "There were just so many elements to it—looking at the past, scenarios for the future, looking at forest conditions versus rare plants versus invasive species. How to organize all those thoughts? We were bumbling with it. Teresa was able to get her arms around where the overall assessment was going, and put the vegetation chapter into a form that people could digest."

Hollingsworth, Tara Barrett (a Pacific Northwest Research Station research forester) and colleagues from several research agencies and the University of Alaska used computer models to explore potential outcomes across Alaska for the next 5 to 6 decades for various vegetation types, including invasive species. They found that some forest habitats are more likely to undergo change than others. For example, the distribution of coastal rainforests and Sitka spruce will likely be minimally affected by projected changes in climate. On the other hand, forest types on the western Kenai are likely to decrease. In particular, white spruce abundance is expected to drop because of climate change in combination with climate-related increases in spruce bark beetle outbreaks. Of paramount concern, the authors noted, is the potential loss of alpine tundra and associated rare species.

Another concern they raised is the Kenai Peninsula's vulnerability to wildfire. In general, fire hazards are likely to increase. Hollingsworth and co-author Matthew Berman from the Institute for Social and Economic Research took the analysis one step further and looked at the potential economic impact of fire on the Kenai Peninsula. Berman modeled future property development to 2065 and projected a total value of $1.8 billion for structures in "extreme" wildfire risk areas, with an additional $2 billion for structures in "high" wildfire risk areas.

The vulnerability assessment gave the Chugach National Forest planning staff a sturdy science foundation as they prepared to revise their forest plan. "The authors of the assessment kept the forest apprised of what we were finding all along as we wrote the chapters," said Hayward. "I would give overviews to forest leadership as we progressed so that the process of assessing vulnerability of key resources was getting braided together with the initial steps of developing the forest plan revision. It was a strong science-management partnership."

Alaska's early warning

Alaska and other northern latitudes are at the tip of the spear as climate change causes forests around the world to adapt to a new and sometimes unprecedented set of conditions. Plants in the Arctic tundra are blooming earlier. The Iditarod sled dog race has had to move its starting line north in search of snow. Coastal villages are struggling to relocate. Fires are burning bigger and hotter in the interior boreal forest system. As permafrost thaws, "drunken forests" are becoming a common sight. The thawing ground causes trees to tilt and slump over, a phenomenon that can be detected through remote sensing (see sidebar on page 12). Permafrost thaw is also causing sections of the Alaska Highway, the 1,387-mile artery connecting Alaska to Canada and the northwestern U.S., to buckle.

A Bonanza Creek Long-Term Ecological Research study by April Melvin, a policy fellow at the American Association for the Advancement of Science, found that climate-related damages in Alaska could reach $5.5 billion from 2015 to 2099 in the form of road flooding, damages to buildings associated with permafrost thaw, and destruction to railroads, pipelines, and airports. The

Bureau of Land Management

Climate change has forced the famous Iditarod sled race to move its start to Fairbanks twice in the past 5 years due to lack of snow at its traditional start 350 miles to the south.

study suggested that reducing greenhouse gas emissions could lessen damages by $1.3 billion this century.

Hollingsworth is aware that the research coming out of Bonanza Creek could be influential as other parts of the world catch up with the pace of change in Alaska. "As we are seeing temperature rise faster here than anywhere else in the world, it has become clear that we have this great opportunity to contribute on a much more global scale than we initially thought, just in terms of the importance of the boreal forest in storing carbon, the permafrost thaw, and the very extraordinary change in fire regime. We have really tried to think about how our research is contributing to a more global framework for understanding climate change."

Lynn D. Rosentrater

"Drunken trees" are a sign of permafrost thaw. Trees like the black spruce adapted to growing on frozen ground and have no significant taproot to help anchor them. Thawing permafrost undermines the shallow root bed of these trees, causing them to lean or fall.

Situated thousands of miles away, it can be easy for those in the lower 48 states to ignore the signs and warnings coming from Far North Alaska. But given the global consequences for the carbon cycle, what happens in Alaska doesn't stay in Alaska.

For millennia, the permafrost of the Arctic and boreal regions acted like a giant freezer, locking carbon in place. In the boreal forests of North America, the carbon store is equivalent to 26 years of global emissions from burning fossil fuels. Some of this carbon has been there for 8,000 years. How long will it stay in the ground? According to the National Oceanic and Atmospheric Administration, in 2016, permafrost temperatures were the highest on record at the majority of Arctic observation sites.

In the fall of 2018, Alaska was locked into an unusually warm pattern that shattered records for the latest first freeze and snow of the season in some parts. By mid-October 2018, Fairbanks was still waiting for its first snowfall of the year, which usually happens by October 1.

The first significant snowfall of the year hit Fairbanks on October 19, breaking the record for the latest first snowfall.

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Science Update

U.S. Department of Agriculture
Pacific Northwest Research Station
1220 SW Third Avenue, Suite 1400
P.O. Box 3890
Portland, OR 97208-3890

SUMMARY

The Arctic and boreal regions are warming more than twice as rapidly as the rest of the world. The timing of plants' flowering and fruiting is changing, with implications for insects, wildlife, and people who rely on these resources for food and livelihoods in Alaska. Alaska's boreal forest will undergo significant functional and structural changes within the next few decades that are unprecedented in the past 6,000 years. The Bonanza Creek Long-Term Ecological Research program is critical to Forest Service research because it is the only Forest Service outpost in the boreal forest, which is the biggest forest in the world. Pacific Northwest Research Station scientists are contributing groundbreaking climate research in Alaska, with global implications.

Contacts:

Janet Prevéy, research ecologist, U.S. Geological Survey, jprevey@usgs.gov

Teresa Hollingsworth, research ecologist, U.S. Forest Service, Pacific Northwest Research Station, teresa.hollingsworth@usda.gov

Hans Andersen, research forester, U.S. Forest Service, Pacific Northwest Research Station, hans.andersen@usda.gov