Arctic Plants

Global warming is dramatically revamping not only the ice
greening some parts and browning others. The alterations

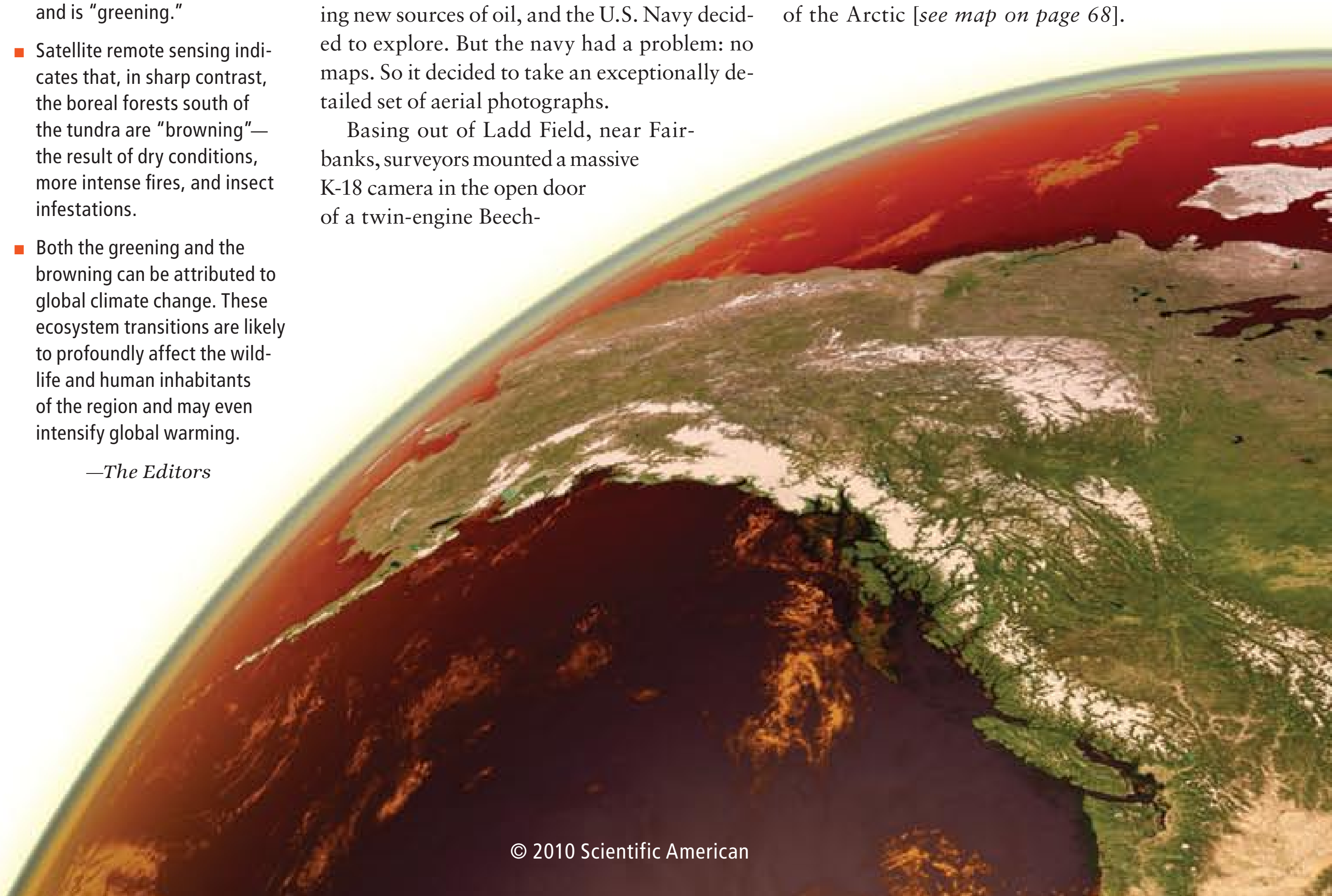
KEY CONCEPTS

- A detailed set of aerial photos taken in the 1940s for oil exploration in northern Alaska has provided the most graphic evidence that the Arctic tundra is turning shrubbier and is "greening."
- Satellite remote sensing indicates that, in sharp contrast, the boreal forests south of the tundra are "browning"—the result of dry conditions, more intense fires, and insect infestations.
- Both the greening and the browning can be attributed to global climate change. These ecosystem transitions are likely to profoundly affect the wildlife and human inhabitants of the region and may even intensify global warming.

—The Editors

The year was 1944. World War II was showing signs of winding down, but predictions that the Japanese would fight to the bitter end had the Allies gravely concerned that they would run out of gasoline for the war effort. The 23-million-acre Naval Petroleum Reserve in northern Alaska was a prime location for finding new sources of oil, and the U.S. Navy decided to explore. But the navy had a problem: no maps. So it decided to take an exceptionally detailed set of aerial photographs.

Basing out of Ladd Field, near Fairbanks, surveyors mounted a massive K-18 camera in the open door of a twin-engine Beechcraft. Over several years, flying low and slow, they took thousands of photographs of Alaska's North Slope, extending from the Arctic Ocean south to the Brooks Range, and of the forested valleys on the south side of the range—itself a part of the boreal forest of evergreens and deciduous trees that stretches across a large swath of the Arctic [*see map on page 68*].



Feel the Heat

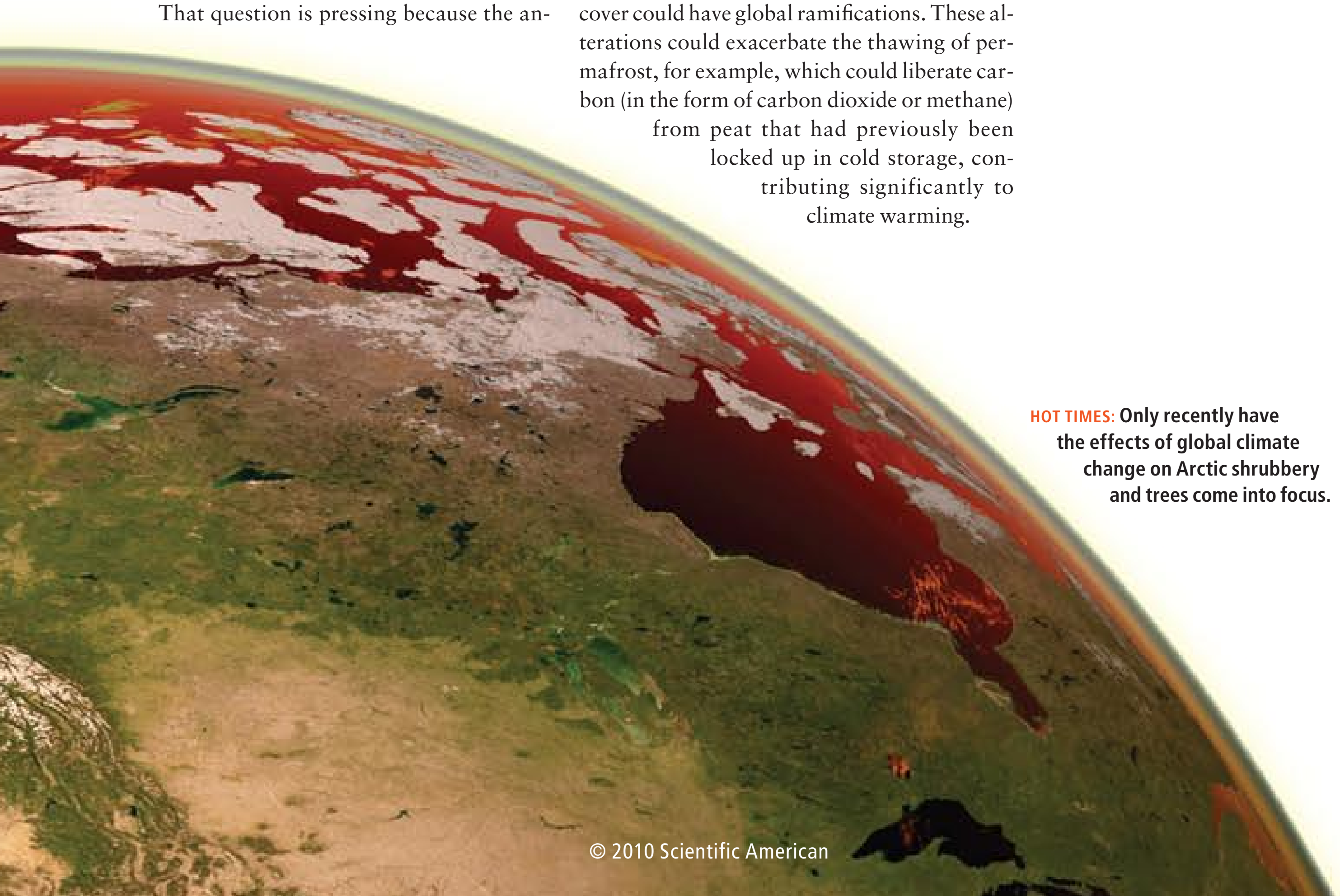
but also tundra and forests at the top of the world, could exacerbate climate change

By Matthew Sturm

The nine-by-18-inch negatives produced pictures so sharp that hoofprints of moose were visible. Some images were worthy of Ansel Adams, but more important, the full set has proved to be a crucial part of the evidence revealing how Arctic and sub-Arctic lands have been responding to climate change.

That question is pressing because the answers will help local inhabitants figure out what steps they need to take to cope with the changes. Approximately four million people live in the Arctic, and the climate shifts are affecting subsistence hunting, commercial logging, transportation and infrastructure.

Moreover, unexpectedly fast changes in land cover could have global ramifications. These alterations could exacerbate the thawing of permafrost, for example, which could liberate carbon (in the form of carbon dioxide or methane) from peat that had previously been locked up in cold storage, contributing significantly to climate warming.

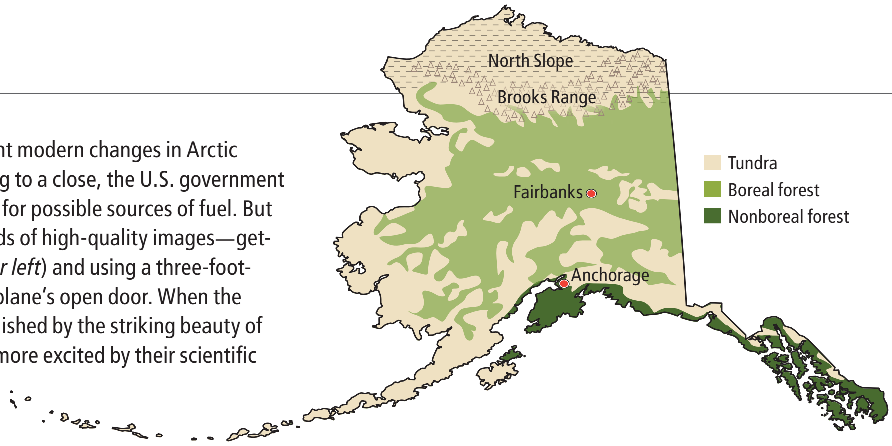


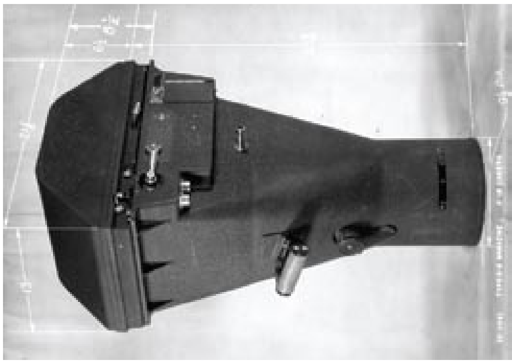
HOT TIMES: Only recently have the effects of global climate change on Arctic shrubbery and trees come into focus.

[HELP FROM HISTORY]

Sixty Years Ago

A World War II–era project has inadvertently helped document modern changes in Arctic vegetation. Worried about oil supplies as the war was drawing to a close, the U.S. government decided to survey Alaska's North Slope (*dashed area on map*) for possible sources of fuel. But no useful maps existed. So U.S. Navy surveyors took thousands of high-quality images—getting the shots by flying low in a twin-engine Beechcraft (*lower left*) and using a three-foot-long, large-format K-18 camera (*lower right*) mounted in the plane's open door. When the author obtained the photographs decades later, he was astonished by the striking beauty of many of them (*example at bottom of page*). But he was even more excited by their scientific import: he and his co-workers went on to reshoot the same locations and compare the images, thereby documenting profound changes in the vegetation.





How to Measure Greening

Even before a polar bear on a tiny ice floe made the cover of *Time* magazine in 2006, it was clear that the Arctic sea ice was melting rapidly [see "Meltdown in the North," by Matthew Sturm et al.; Scientific American, October 2003]. By the 1990s those of us who study climate change in the Arctic had good reason to think that Arctic vegetation was also changing, but our tools for tracking terrestrial alterations were not as effective as those for sea ice. White sea ice contrasts starkly with dark ocean water, which makes the ice and water amenable to monitoring from satellites and airplanes. In contrast, climate-driven variations in tundra—treeless regions where the subsoil is permanently frozen—and forest can be subtle, sometimes just a slow alteration in the mix of plant species rather than a sharp shift from one type of ecosystem to another. Vegetation changes can take years, even decades, before they become detectable.

We did have strong hints about what type of changes to look for, however. Greenhouse experiments on the tundra had shown that fertilization and artificial warming of the soil could produce dramatic growth of shrubs at the expense of nonwoody tundra plants such as sedges and mosses. Dwarf birch plants, for example, that had previously been knee high grew to head height in a matter of years. Based on this evidence, our best guess was that tundra warming would trigger an increase in biomass, possibly an explosive one—mainly in the form of more and bigger shrubs. Farther south, in the boreal forests, the tree line had been advancing both northward and upslope to higher altitudes for centuries. The expectation was that warming would accelerate this march.

But nothing was certain. At the time, various research groups were trying to detect shifts in vegetation using remote sensing or intensive studies of small plots on the ground, so my colleagues Chuck Racine and Ken Tape and I reasoned we could best contribute new informa-

JEAN-FRANCOIS PODEVIN AND NASA (*preceding pages*); JESSICA HUPPI (*map*); AP PHOTO (*airplane*); COURTESY OF NATIONAL MUSEUM OF THE U.S. AIR FORCE (*camera*) tion by looking for change using old photographs—if we could find such documents. During our search, an archivist mentioned that he had some navy air photos from the 1940s in his warehouse. Were we interested? He was planning to throw them away soon because of limited storage space. I held my breath until a sample arrived. As the photos slid out of the envelope onto my desk, I was stunned. They were perfect for our work, and they were beautiful. Eventually we had about 6,000 on our shelves.

In the summer of 2000 we began our study, concentrating on the tundra. The definition of tundra, with its low-growing vegetation and permanently frozen subsoil, does little to convey the great beauty and complexity of this ecosystem. Covering about 5 percent of the earth's land surface, most tundra is a thick carpet of mosses, lichens and sedges (which look like grasses), with a smattering of other vascular plants and dwarf shrubs. From the air this collection of plants appears to be a low green carpet, plush and smooth. On the ground, it is a mosaic of many plants, all spongy and tiring to walk on, although when dry, delightful to lounge on. And it is anything but flat. The sedges and other plants grow into bumps called tussocks, or hummocks, that are the bane of anyone who has tried to walk far over the tundra. Rising up to half a meter high, these bumps are often unstable at the top, flopping over when weighted and sending hikers tumbling to the ground or twisting their ankles. Typically the dwarf shrubs hide in the creases between tussocks, although dense patches of head-high shrubs often cluster near water.

The higher the latitude, the more barren the tundra becomes, until the shrub component vanishes. Finally, even the mosses and lichens give way to vast areas of bare soil, known as polar desert. To the south, the tundra transitions first into a smattering of spruce trees, then into a patchwork of tundra and forest, and finally into the boreal forest, also called taiga. The transition from tundra to taiga can be abrupt, or it can spread over tens of kilometers. In Alaska the boundary is largely coincident with the southern edge of the Brooks Range.

To take the repeat photos we needed, we flew in a helicopter with the doors off, armed with copies of the old photos. Circling until we could match the earlier view as closely as possible, we often found ourselves barely 15 meters off the deck, a revelation that gave us added respect for our World War II predecessors in their fixed-wing plane. With care, we could achieve a fairly close match. Over four summers we rephotographed more than 200 locations. In the evenings we would compare the new photos with the old for an informal assessment. In image after image, individual shrubs were bigger than they had been 50 years earlier (yes, individual shrubs were still alive and identifiable!). Patches of shrubs had filled in, and the patches had expanded into tundra where shrubs had previously been smaller than our detection limit of about 50 centimeters high. Willow, birch and alder, the big three of Arctic shrubs, were all expanding in range and getting larger. We were particularly impressed by one pattern of shrub advance we nicknamed "shock troops," where shrubs had colonized old river terraces and tundra flats, taking over hectares of previously shrub-free territory in a few short decades.

The reality of the transformation was driven home when we field-checked the photos. Shrubs that appeared in our new photos as small dark circles proved to be as tall as a person. These were often ringed by halos of smaller shrubs, which the larger bush appears to protect from harsh winds and blowing snow. In some places, the shrubs were so thick they formed impene-

ARCTIC LINGO

Albedo: The extent to which an object or surface reflects light from the sun. Snow and ice are superior reflectors. They return to space up to 85 percent of sunlight, thus limiting warming of the land.

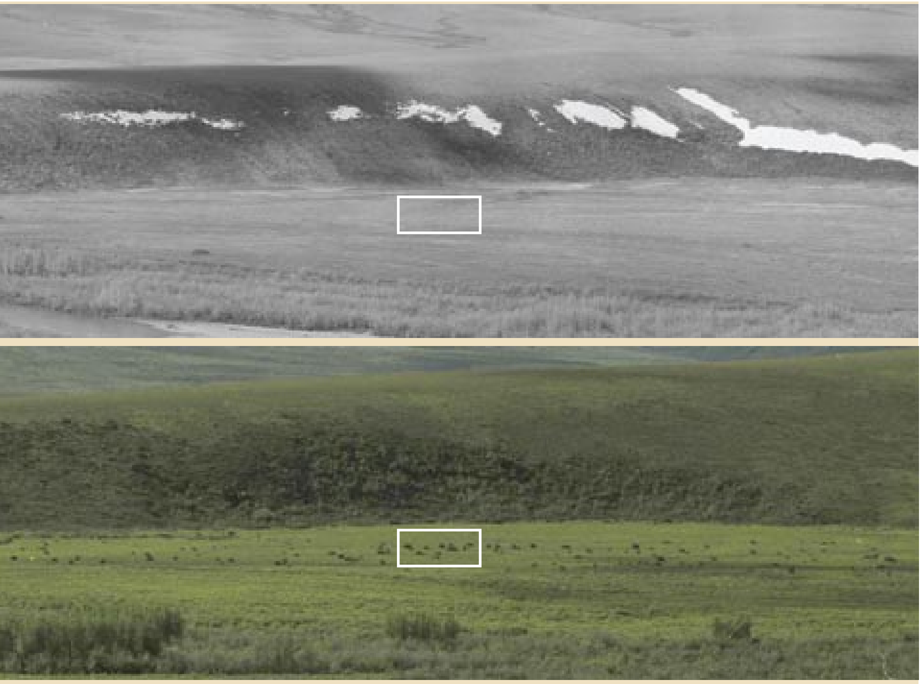
Taiga, or boreal forest: The forests in and just south of the Arctic Circle; they consist mainly of conifers and constitute the world's largest ecosystem.

Tundra: Treeless region in the Arctic where the subsoil is permanently frozen, and the ground is covered by dense, low vegetation.

To see other striking images from the U.S. Navy survey, visit **www.ScientificAmerican.com/arctic-plants**

COURTESY OF U.S. NAVY

PHOTO FROM 1940S, **taken by U.S. Navy surveyors, shows gullies along the Colville River filled with drifted snow from the winter.**



COMPARISON of photographs taken of Alaska's North Slope in the 1940s and at the same time of year early in the 21st century presents graphic evidence of an increase in plant growth. The color image, from 2002, highlights human-height "shock troop" shrubs marching across a tundra terrace where they were originally absent.

Climate shifts in the Arctic are affecting hunting, logging, transportation and infrastructure locally and exacerbating warming worldwide.

trable thickets. By the end of the second summer, after we had thrashed our way through dozens of shrub jungles, we coined the phrase "shrubby Arctic" to capture what was happening to the landscape. In all, the photos documented that shrubs had been expanding in an area of northern Alaska measuring more than 200,000 square kilometers.

But what was happening to the tundra outside of Alaska and in the taiga forests to the south? To answer this question, my colleagues Scott Goetz, Doug Stow, Skip Walker, Gensuo Jia and Dave Verbyla were using the radiometers on NOAA weather satellites to measure changes in those sites as well as in Alaska. Computing an index called NDVI (normalized difference vegetation index) based on reflectance in the red and near-infrared bands, they were finding that the greenness of the tundra was increasing. Greenness correlates with biomass and new growth, and the researchers interpreted their findings to mean that the shrub component of the tundra was expanding. The increase in NDVI was most pronounced in Arctic Alaska, western Canada and Siberia but could be detected in Scandinavia and other parts of the Arctic as well. Other colleagues—Bruce Forbes in Russia, Greg Henry in the Canadian High Arctic and Paul Grogan in central Arctic Canada—were finding similar results from their on-the-ground studies, while the recollections of Arctic residents in Alaska, Canada and Russia added support to the idea that a pan-Arctic increase in shrubs was under way.

A close comparison of the most recent satellite record of tundra greening with our photo-based map of shrub change provides one additional detail: the NDVI is increasing not only in the tundra areas where the photos show more large shrubs but also where only dwarf shrubs (below the photo detection limit) can currently be found. These small shrubs between tussocks are ubiquitous, and they are plastic: they can alter their growth form when growing conditions improve, attaining substantial size. With mini shrubs already in place over a vast area, the tundra regions are preconditioned for rapid growth.

Such a phenomenon would not be unprecedented. The paleo-record—pollen found in sediment cores—shows an abrupt increase in shrub pollen about 8,000 years ago. Known informally as the "birch explosion," it seems to mark a time when shrubs swept across the tundra landscape.

A Surprise in the Forest

The satellite records revealed an even more startling result in the vast boreal forests south of and ringing the tundra. Although studies confirmed that the tree line was continuing to move northward and to higher elevations, in many places the satellites indicated that behind this advancing front the forests were losing biomass and becoming less productive. The forests were browning—drying and dying—while the tundra was greening, a fact that seems to contradict the conventional wisdom concerning the forest response to climate warming.

About 10 years ago Glenn Juday and Martin Wilmking, then at the University of Alaska Fairbanks, started collecting a set of tree ring samples from near Fairbanks and south of the Brooks Range that have helped unravel the apparent contradiction. Instead of the customary positive correlation—higher temperatures in summer produce better growth and wider rings—they began to find stands in which higher temperatures had produced smaller rings and more slowly growing trees. In western Alaska, where it was wetter, they found the trees grew more vigorously as it warmed, but as they moved east into drier country, they discovered smaller rings, distressed trees and struggling, even dying, tree

COURTESY OF U.S. NAVY (*top landscape comparison*); COURTESY OF KEN TAPE (*bottom landscape comparison and scrub halo*); COURTESY OF GASIUS R. SHAVER *Marine Biological Laboratory* (*greenhouse structure*) stands. The warmer summers were just too dry.

Two other dendrochronologists, Andi Lloyd of Middlebury College and Andy Bunn of Western Washington University, using every boreal tree ring record they could uncover, confirmed that the browning of the boreal forests was a pan-Arctic phenomenon and that although it predominated in spruce trees, it occurred in all boreal tree species. The exact causes of the declining tree growth are still being worked out, but drought and heat stress are two primary suspects, because browning has been observed more commonly in dry continental sites and in the southern part of each species' range.

The trees have been getting hammered in two other ways as well, both thought to be linked to the warming climate—increased insect outbreaks and a rise in the frequency and size of forest fires. In Alaska, big forest-fire seasons seem to be coming about every five years rather than every 10, and infestations of insects such as the spruce bark beetle, which have ravaged more than 500,000 hectares of prime forest in Alaska so far, appear to be intensifying.

Predicting the Future Is Hard to Do

The changes taking place on the tundra and in the boreal forests present an ironical symmetry. The boreal forests have encroached on an estimated 11,600 square kilometers of the southern edge of the Alaskan tundra in 50 years, yet over the same period they have been drying out, burning up and suffering insect damage behind their advancing front. Juday and others suggest that the outcome is going to be a conversion from forest to grassland. At the same time, the tundra is becoming increasingly shrubby and junglelike. Does the future have in store a switch, where the forest will begin to look a lot like tundra, while the tundra looks more and more like forest?

The problem with answering this question is our limited ability to understand the linked processes that are driving the vegetation changes, let alone predict their future course. Even though the Arctic sea ice is a simple system of just water and ice that responds in principle to physical rules that can be coded into models, the ice has been declining at a rate that is twice as fast as that predicted by 13 of the scientific community's best large-scale models. Current predictions are for an ice-free Arctic Ocean in 40 years, but these predictions are more extrapolations of observed changes than model results. For the tundra and boreal forests, with their great biological complexity and competing feedback mechanisms—some that dampen growth and some that accelerate it—the existing models are still too simplistic to produce accurate predictions.

In a recent paper, my group tried to address the prediction question for tundra shrubs using a simple model of shrub population growth and the contrasting photos. To our surprise, the model indicated that the shrub expansion started about 150 years ago, near the end of the Lit-

My gut feeling is that the tundra landscape is likely to change faster than predicted by our crude model.

EXPERIMENTS and observations support the photographic evidence that the tundra is becoming shrubbier. In greenhouse studies that artificially warmed the soil (*below;* greenhouse covering has been removed), shrubs grew to head height, while those in normal soil stayed about knee high. And observations in nature (*right*) indicate that bigger shrubs, in a so-called halo effect, protect smaller ones from the elements and thus encourage growth in concentric rings (*marked by lines*) around a big one—resulting in a much greener tundra.

[THE AUTHOR]

Soon after completing a doctorate at the University of Alaska Fairbanks in 1987, **Matthew Sturm** went to work for the U.S. Army Corps of Engineers, where he is a research scientist. Recently he led a 4,000-kilometer snowmobile traverse across Alaska and Arctic Canada. Sturm's interest in shrubs and trees developed during an earlier trip, when he got stuck in deep snow in a willow patch. After several hours of tugging on snowmobiles and packing down snow, he realized that maybe the shrubs had an impact on snow cover—which ultimately led to the studies reported in this article.

tle Ice Age. We had expected the expansion to correspond with the rapid Arctic warming that has taken place since the 1970s. On the other hand, the timing coincided nicely with the first appearance of moose, those long-legged shrub browsers, on Alaska's North Slope. It also coincided with the onset of tree line expansion.

The model results imply that, in part, the shrubs have been slowly expanding in response to a natural warming cycle that began well before the industrial revolution. Other lines of evidence, however, suggest that although this expansion probably started because of natural warming, it is continuing, and apparently accelerating, because of human-aided warming. In the region where shrubs are expanding, the past four decades have also seen a marked increase in the retreat of glaciers, an increase in the rate of permafrost warming and an advance in the onset of spring (as revealed by freeze-up and break-up dates for rivers and lakes)—all of which have been tied to climate change accelerated by human activities. Sadly, we are unlikely to find a set of photos from the 1900s, which is what we would need to establish that the rate of shrub expansion was slower between 1900 and 1950 than between 1950 and the present.

BIG FOREST-FIRE SEASONS in Alaska now seem to come much more frequently, and the fires are more intense. Fires and insect damage together are browning the once green boreal forest. Shrubs thrive in these burned areas and, with their greater biomass and branching, increase the possibility of still more fires in the future.

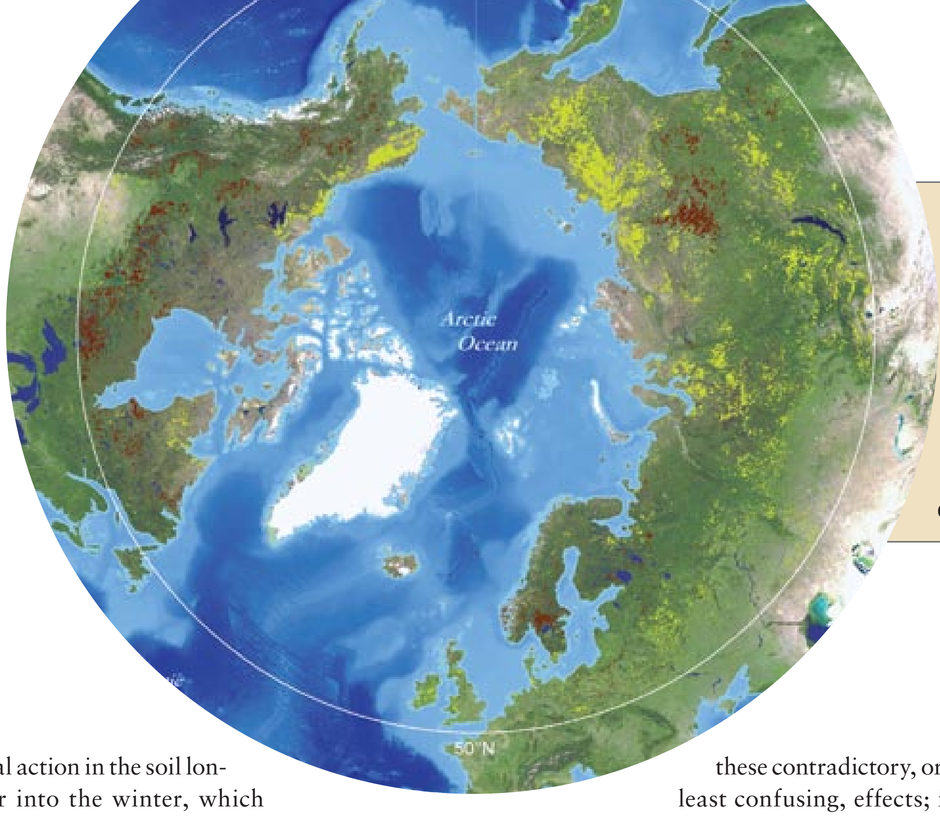
The same simple model predicted that it will take at least 150 years before shrub-rich areas are completely covered with shrubs; where there are no shrubs now, it will take even longer. The danger with trusting this prediction, though, is that the model does not allow for catastrophic effects such as fire that might abruptly alter the vegetation (shrubs tend to thrive in disturbed areas), nor does it include feedback effects that might speed up the change. My gut feeling is that our prediction is too conservative and that the tundra landscape is likely to change faster than predicted by our crude model.

One source of this suspicion is the aftermath of actual fires. From July to September 2007 during exceptionally dry weather, for example, the largest lightning-caused tundra fire on record burned on the North Slope, scorching more than 100,000 hectares. My colleague Chuck Racine visited the area in July 2009. In many places, shrubs had already resprouted. In similar, older tundra burn areas in western Alaska, shrub cover expanded by as much as a factor of eight in 30 years. Increasing lightning strikes and drying conditions could lead to more fires. Moreover, the shrubs, with their greater biomass and branching, increase the likelihood of fire in the future, creating a positive feedback effect.

Of the other potential feedback effects that operate on the tundra, we know of at least two positive ones related to the winter snow cover. It may seem strange to think of winter having any impact on the growth of shrubs, because they do their growing in the summer, but winter processes determine soil and water conditions for the following growing season. The importance of winter to Arctic plants lies in its long duration. The tundra is covered by snow nine months of the year and the taiga seven months, making the predominant color of these regions white, not green.

One of the feedback processes works like this: where shrubs manage to overtop the nearby tussocks, they trap snow in the winter, producing drifts that deepen the snow cover around them. Snow is an excellent insulator, nearly as good as a down quilt (this is because the snowpack may be as much as 75 percent air). Where the deeper snow insulates the ground better, soil temperatures are higher than they would otherwise be. In some shrub zones we have found temperatures at the base of the snow to be 10 degrees Celsius greater than in adjacent tussock areas. The warmer conditions promote micro-

COURTESY OF MATTHEW STURM (*Sturm*); ALASKA STOCK (*fire*)



MAP OF THE ARCTIC, based on satellite data collected and analyzed by Scott Goetz and his colleagues at the Woods Hole Research Center, reflects changes in the state of the tundra and boreal forest between 1982 and 2005. Consistent with other work, the analyses show that shrub growth increased (*light green areas*) and that the forest underwent drying and tree losses (*brown areas*).

COURTESY OF SCOTT GOETZ *Woods Hole Research Center*

bial action in the soil longer into the winter, which stockpiles more nutrients so that come summer, the shrubs get a boost. Fertilized shrubs grow vigorously, so they become taller, thereby trapping more snow in the ensuing winters, reinforcing the cycle.

The other snow-related feedback effect derives from the albedo (reflectivity) of the snow. The dark branches of tall shrubs protrude above the snow during winter and particularly in spring. These branches absorb solar energy many times better than the white snow, enough to cause local warming and accelerated melting in the spring, producing an earlier start to the growing season and stimulating the shrubs to grow larger still.

Individually, the winter feedback effects are easy to understand, but because they are not independent of one another or of summer processes (some of which are well understood, others not), the net effect is uncertain. For example, the deeper drifts produced by shrubs should in principle take longer to melt in spring than the surrounding undrifted snow. Can the albedo effect overcome the enhanced depth effect, or does the drifting trump the accelerated melting? In summer, shading and leaf litter are two potential feedback processes not fully understood. Shading by an enhanced shrub canopy is known to produce lower summer soil temperatures, potentially working against the winter snowdrift enhancement of microbial action. Leaf litter from the shrubs alters the nutrient loading around the shrubs, potentially spurring growth.

Many investigators are busy trying to model these contradictory, or at least confusing, effects; indeed, several groups are developing predictive models of tundra and boreal forest change. But one of the biggest wild cards in their deck is whether the future climate will bring more snow or less. If this terrestrial science follows the example of efforts to understand the vanishing sea ice, it will be our ability to physically track the ongoing changes and project those into the future, rather than computer models alone, that will answer the big questions. Not surprisingly, photograph pairs from Alaska are being used as test data in model development.

We were certainly lucky that the navy took exceptional photos on Alaska's North Slope—and that we managed to get our hands on them. Serendipity is as important in science as in other aspects of life. Had we not found the photos, we might not have realized as soon as we did that a transformation in landscape potentially as profound as the loss of sea ice was taking place in front of our eyes. The photos are the most graphic and easily comprehended evidence, although without satellites and the careful work of dendrochronologists, we would not know other parts of the story.

The challenge now is to work out a method to predict what will unfold on Arctic lands and how fast. The complexity of biological systems makes the task difficult. Nevertheless, if we do not do it quickly, the changes are likely to overtake us, forcing us to react rather than anticipate. I am fairly certain now, however, that this story is being played out in three colors: green, brown and white. ■

➥ MORE TO EXPLORE

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