Ecology

Beloved Arctic Station Braces for Its Own Climate Change

Researchers of all stripes have been monitoring the impact of climate change at Alaska's Toolik Lake for decades. They now face new challenges

Toolik Lake, Alaska—Lying on his stomach, ripping moss off a two-by-three-meter patch of tundra, Tom Crumrine learned this summer what it means to study climate change in the Arctic. The high school teacher from Concord, New Hampshire, spent 3 weeks of his break on a fellowship at the Toolik field station on Alaska's North Slope, contributing to an experiment on how changes in vegetation caused by global warming will affect the Arctic landscape.

The answers won't be clear for years to come. But delayed gratification is the norm at Toolik Lake, where for 3 decades scientists have journeyed 300 kilometers above the Arctic Circle to assess the state of flora and fauna as Earth warms. "It's always been a place where you could come and really focus on your work," says Gaius Shaver, an ecologist at the Marine Biological Laboratory in Woods Hole, Massachusetts.

During the short research season, hundreds of ecologists, geomorphologists, plant physiologists, and biochemists traipse out to field sites, some 250 kilometers away, to measure and manipulate nutrients, species composition, temperature, water flow, and other factors. Their observations will be plugged into the still emerging picture of the impact of global climate change on Arctic ecosystems, which are coping with air temperatures that have risen by an average of 3°C in Alaska over the past 40 years.

The research station itself is also changing with the times. Toolik's leaders want to keep the lab open year-round, instead of just 4 months during the late spring and summer. They also hope to improve lab conditions, extend their studies into additional territory, and increase outreach to undergraduates as well as teachers like Crumrine and their students. "The Arctic is such a data-poor place," says Tom Pyle, director of the Arctic research section at the National Science Foundation (NSF), which provides the station with 90% of its $10.5 million in annual support. But its record, he says, makes Toolik "the crown jewel."

However, scientists fear the gem could lose some of its luster. Toolik sits just off the Dalton Highway, a road built and maintained for the oil wells 200 kilometers to the north at Prudhoe Bay, and there are plans for a pipeline to carry natural gas from those same fields. Other proposed developments could also encroach on ongoing or planned experiments. And scientists are worried about NSF's ability to continue to support their work. Flat budgets expected for the agency's 26 ecological research stations, of which Toolik is one, for ecosystems studies and for Arctic research jeopardize existing activities and leave little room for growth.

For science's sake. In June, University of Alaska researcher Syndonia Bret-Harte and teacher Tom Crumrine spent their days pulling moss to simulate potential global climate change effects.

"Our concern is Toolik has a unique dataset that we feel is very important," says John Hobbie, director of the ecosystems center at the Marine Biological Laboratory in Woods Hole, Massachusetts. If funders pull the plug, even temporarily, he warns, decades of work might be lost forever. "We can't reconstruct that data set."

Meager beginnings

It was 30 years ago that Hobbie first recognized Toolik Lake's potential as a research site. He followed the bulldozers as they built the "haul" road northward to bring pipes, gravel, and other construction goods to the oil fields. A 25-meter deep lake perfect for comparing lake and pond nutrient cycles, Toolik allowed Hobbie to further his NSF-funded research on aquatic ecosystems, a project he's continued ever since. A year later, Shaver showed up to study revegetation of the roadside, helping to establish a terrestrial complement to Hobbie's work.

With the Brooks Range as a backdrop, researchers at Toolik make use of continuous sunlight during the summer to work alongside caribou, bear, and moose on one of the world's most carbon-rich soils. Arctic tundra and boreal ecosystems take up one-sixth the world's land, but possess one-third the world's terrestrial carbon. Within hiking distance are tundra habitats ranging from wet soils covered with squishy moss to dry heath landscapes. The age of the land varies from 12,000 to 200,000 years, making the area a good place to understand how soils contribute to tundra ecology.

In 1987, the field station became an NSF Long-Term Ecological Research (LTER) site, directed by Hobbie. NSF core funding, now $820,000 a year, provides for technicians and equipment to help keep long-term studies going with or without income from individual investigator grants. The site put down even deeper roots in 1999, when NSF signed a cooperative agreement with the University of Alaska to run the station. A new 5-year agreement starting next year will provide about $1.5 million per year.

For years the lab grew slowly, retaining its rustic atmosphere. Two trailers served as kitchen, dining area, office, and lab. Scientists slept in backpacking tents. Today, there are four custom-built doublewides for labs, a dining hall open 24-7, a trailer for showers, and even one for laundry—32 buildings in all. There's a helicopter, and a fiber optic line put in for the Alyeska Pipeline Company of Anchorage provides Internet access. "They have put a lot of money into getting a really high-tech infrastructure," says Jeff Dudycha, an evolutionary biologist at William Paterson University in Wayne, New Jersey, who visited Toolik this summer as

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part of a field trip arranged for the Evolution 2005 meeting in Fairbanks. Adds Breck Bowden, an aquatic ecosystems ecologist from the University of Vermont, Burlington, "We have lab facilities that rival what I have [at my university]."

The terrestrial research at Toolik consists in large part of parallel experiments in different types of tundra. Plots are fertilized with either nitrogen, phosphorous, or a mixture of both. Some are housed in plastic greenhouses that boost ambient temperatures by an average of 3.5°C and simulate global warming, while others are shrouded in layers of greenhouse shade cloth that block half the incoming light. Fine chicken wire helps exclude small herbivores, and taller fences keep out moose and caribou.

The message from all these experiments is clear: The availability of nutrients is the driving force for the ecosystem. With the light cut by 50%, "there isn't much impact," says Shaver—at least not right away. The same is true for temperature. On acidic, 60,000-year-old tundra that has been fertilized, stands of dwarf birch eventually dominate, replacing sedges. The birch trees use added nutrients to grow taller and bushier, blocking ever more light from competitors. The shrub cover also insulates the ground, altering the season during which decomposition—and the release of nutrients—can occur.

In 2004, Shaver and his colleagues reported the surprising result that supplementary nitrogen and phosphorous fertilizer had increased plant production but resulted in a net loss of nitrogen and carbon from deeper layers of acidic soils. When exposed to fertilizer, soil microbes boosted their breakdown of the organic matter in those layers. Moreover, fertilizer increased the rate at which organic nitrogen was converted to an inorganic form. He also learned that productivity in greenhouse plots can change: It took 9 years to see an increase in productivity in the unfertilized greenhouse plots, as the increased temperature slowly boosted microbial activity and the release of nutrients locked up in the soil. "The message I get is to be careful about jumping to conclusions," says Pyle.

Research on streams and their role in nutrient flow is also yielding surprising results. In 2003, Bowden and hydrologist Michael Gooseff from the Colorado School of Mines in Golden began tracking the course and nutrient flow of subterranean water percolating along streambeds. They discovered that this submerged waterway and its surroundings—called the hyporheic zone—play a bigger role in stream ecology than had previously been thought. "We suspect that a major part of the nutrients to supply primary productivity actually come from [this] zone and not from the [nutrients] that run off the landscape directly," says Bowden.

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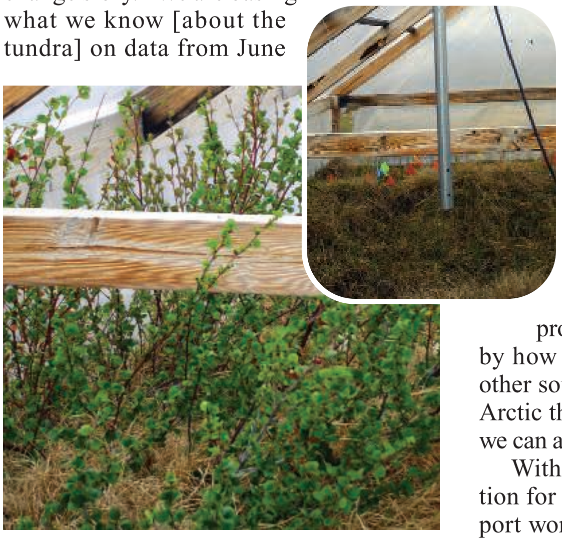
Scenic science. With Alaska's Brooks Range as a backdrop, Toolik research station stands out as a center for studying global change in the Arctic.

The researchers also are finding that the hyporheic zone holds steady at 2° to 3°C below zero, and the ice above gets no colder despite air temperatures of minus 50°C. "So it only took a little bit of exposure to sunlight" to start the water flowing again, says Bowden. "The whole system is primed to go" as soon as the sun returns to the sky, he adds.

Opportunities and threats

Despite their concentrated efforts each summer, scientists are concerned that they might be missing part of the climate change story. "We are basing what we know [about the tundra] on data from June and July," says Brian Barnes, director of the University of Alaska Institute of Arctic Biology, Fairbanks, which runs the Toolik station. "We've been assuming that nothing is happening in the winter because it's too cold." But work by researchers such as Bowden is showing that underground temperatures may actually be mild enough to allow organisms to function and be on call for the spring.



Nutrients matter. A comparison of fertilized (*above*) and unfertilized (*inset*) greenhouse plots shows the importance of nutrients.

The lab is also trying to add educational components to its research agenda. Crumrine is part of an NSF-sponsored program to provide teachers with research experience in the Arctic. There's talk about starting a graduate student summer course. Also, Robin Bingham, an evolutionary biologist from Western State College in Gunnison, Colorado, is part of a group planning an Arctic biology course for undergraduates.

But such activities require additional resources, which are in short supply. The future of Toolik is closely tied to the future of NSF funding. The agency's overall budget was reduced this year and seems unlikely to do better than inflation in 2006. Forest ecologist Henry Gholz, who manages the LTER program, says both his budget and funding for ecosystems research will "likely remain static or only have a small increase." Another problem is that LTER sites are judged by how well they leverage funding from other sources. But as Hobbie notes, "in the Arctic there are no other agencies to which we can apply for funds."

Within NSF, there is increased competition for funding within programs that support work done at Toolik station. Over the past 5 years, the success rate for ecosystems proposals has fluctuated between 18% and 14%, says NSF's Michelle Kelleher. Success rates for the Office of Polar Programs have gone up and down as well: In 2000, it was 37%, but in 2005 it was 31%. The office is helping to sponsor the International Polar Year in 2007, a global effort to stimulate more research in the Arctic and in Antarctica. Without more money, Pyle says, any initiatives for the polar year will have to be paid out of the

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same budgets as for Arctic and Antarctic research and logistics.

There are non-fiscal threats as well. A natural gas pipeline, if it's built, would mean more people, more traffic, more way stations, and more gravel excavation. One of Shaver's sites is right next to an old gravel pit that, if reactivated, could destroy the site either directly or by increasing silt and other runoff sufficiently to invalidate longitudinal studies.

To counter these possible problems and more, Barnes and his colleagues at the University of Alaska are beginning to seek support from federal and state officials for a 44.5-hectare research park that would protect the study plots against potential intrusions. The U.S. Bureau of Land Management leases 10.8 hectares to the University of Alaska Institute of Arctic Biology as the station's grounds and has zoned the 31,000 hectares around Toolik Lake as a Research Natural Area. Expanding the size of the protected zone to include the upper Kuparak River watershed, a site of some long-term studies, would safeguard research without impeding oil and natural gas development, says Barnes.

It would also protect Toolik's future and avoid, in Gholz's words, NSF's having made "a huge investment that's thrown out." Toolik deserves special attention, Bingham and others would argue, because of its ability to monitor a key component of global climate change. "Arctic ecosystems are some of the most endangered habitats and organisms on earth," she says.

–ELIZABETH PENNISI

Archaeology

Unraveling Khipu's Secrets

Researchers move toward understanding the communicative power of the Inca's enigmatic knotted strings, which wove an empire together

In 1956, Peruvian archaeologists uncovered a vessel hidden in the floor of a high-status home in the Inca administrative center of Puruchuco, near present-day Lima, Peru. Inside, they found a kind of treasure: a set of 21 of the knotted strings called khipu. The Inca relied on sets of khipu (or quipu in Spanish) to keep records of their far-flung realm, which extended more than 5500 kilometers, the distance from Stockholm to Cairo.

The Spanish who conquered the empire discovered that it was held together by a highly efficient bureaucracy that controlled the distribution of labor, goods, and services, using streams of khipu to issue orders and record the results. So essential were khipu to the native population, according to Galen Brokaw, an expert in Andean texts at the State University of New York at Buffalo, that the early colonial government reluctantly approved their continued use until they could be displaced by alphabetic texts the Spaniards could understand. Today, only perhaps 600 pre-Hispanic khipu survive.

For more than a century, researchers have sought to understand how these distinctive objects were used within the empire, and whether they functioned as a unique kind of three-dimensional, textile-based "writing." On page 1065 of this issue, anthropologist Gary Urton and mathematician-weaver Carrie J. Brezine, both at Harvard University in Cambridge, Massachusetts, take a step toward answering both questions. Through a computer-aided analysis of seven of the Puruchuco khipu, Urton and Brezine have identified one way that data and instructions were passed up and down the hierarchy from local villages to the powerful central government in Qosqo (modern Cusco). In the process, they also have tentatively made the first-ever identification of a khipu "word."

Almost simultaneously, archaeologist Ruth Shady Solis of the National University of San Marcos in Lima has independently unveiled what is seemingly the oldest khipu—or, perhaps, proto-khipu—ever discovered. Found in a cache buried inside a pyramid at Caral, an ancient city north of Lima that Shady's team has been excavating since 1994 (*Science*, 7 January, p. 34), the object resembles an Inca khipu, except that the pendant strings are twisted around small sticks.

First strings. This artifact from the ancient city of Caral may be a khipu as old as 4500 years.

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According to Shady, it is more than 3000 years older than the oldest previously known khipu, which date from the 9th century C.E. If so, then khipu, though younger than the world's first writing systems of Sumerian cuneiform and Egyptian hieroglyphics, arose in the third millennium B.C.E. and are among humankind's oldest means of communication.

The Caral artifact's apparent great age of 4000 to 4500 years "indirectly strengthens the case" that the khipu were "more than numeric," notes Daniel H. Sandweiss of the University of Maine in Orono. Ancient writing methods such as cuneiform evolved over many centuries from accounting records, as scribes invented symbols to identify what was being counted. "If what Ruth has found really is a khipu ancestor," Sandweiss says, "then khipu would be following the pattern of other writing systems."

Inca khipu consist of a main cord from which dangle as many as a thousand smaller strings, the latter of which contain clusters of knots. In the 1920s, Leland Locke, an amateur scientist, argued that khipu were simply lists of numbers, with individual knots representing digits and groups of knots on a strand representing successive powers of 10. (Blank spaces function as zeroes.) Locke's rules held true for many khipu, and his view of them as mnemonic devices largely held sway until the 1970s, when the Cornell University husband-wife team of Robert and Marcia Ascher overhauled his work, assembling a detailed khipu database (http://instruct1.cit.cornell.edu/research/quipu-ascher/). They argued that khipu were more akin to writing—and indeed that about 20% of surviving khipu do not fit Locke's rules.

If khipu were a form of writing or proto-writing, they were unlike any other. Scribes "read" the khipu by running their fingers along the strings, sometimes while manipulating small black and white stones—in striking contrast to other cultures' ways of recording symbols, which involve printing or incising