







triggers cellular respiration. The carbohydrate reacts with oxygen to produce water, carbon dioxide, and energy. The carbon dioxide diffuses into the blood and moves to the lungs, where it is exhaled.

Carbon-containing molecules in wood (or other dry, slow-decaying organic materials) may be oxidized by burning, also producing carbon dioxide and water. Under conditions prevailing on earth at certain times, green plants have decayed only partially and have been transformed into fossil fuels—coal, peat, and oil. These materials are made of organic compounds formed by the plants; when burned, they too restore carbon dioxide to the atmosphere.

Under discussion and study today are ways in which

carbon sequestration could be promoted to control the level of carbon dioxide in the atmosphere. There are many gaps in basic scientific knowledge about how ecosystems will behave if temperatures continue to increase in this century, which is predicted. Will the warming of frozen soils promote decomposition and cause the release of more carbon dioxide? Will increased carbon dioxide promote the growth of plants and forests, which could absorb more carbon dioxide? Will warming temperatures retard the growth of some forest species? Some research involves collecting basic data that can be used in conjunction with modeling—computer simulations of climate, plant growth, and other factors in the complex interactions of the carbon cycle.

## Carbon Production in the Boreal Forest

The boreal forest, a circumpolar band that runs through much of Alaska, Canada, Russia, Scandinavia, and parts of northern Scotland, covers seventeen percent of the earth's land surface and accounts for about one third of the planet's total forest area. This extensive eco-region significantly affects Earth's water and carbon budgets, and the related process are now under study around the world. About fifteen percent of the boreal forest is in Alaska.

At the University of Alaska Fairbanks, a computer modeling study by forest sciences professor John Yarie and visiting scientist Sharon Billings developed estimates of net ecosystem production of carbon for Alaska's northern forest. The study produced an estimate of the forest's current standing biomass and carbon content; modeled the current dynamics of the forest carbon; and finally, estimated future carbon dynamics for a scenario in which the mean annual temperature has increased 5° centigrade (9° F).

"The main components of forest carbon dynamics are forest biomass, production, and decomposition of the forest floor and mineral soil organic matter," said Yarie. "The factors that control and change the dynamics of these components are related to climate, plant species, and the structure of the soil organic and mineral soil layers." Biomass is the dry weight of individual components of the ecosystem or, for total biomass, the dry weight of all components.

After creating an estimate of Alaska's forest biomass for each forest type, the study employed CENTURY, a general ecosystem computer model that can simulate nitrogen, carbon, phosphorus, and sulfur dynamics for forests, grasslands, crops, and savannas. It is a stand-growth model that includes belowground vegetation components (roots). The model was previously used for the boreal forest of Alaska in a study by Yarie, et al. (1994). It includes submodels for biophysical processes, plant production, and soil organic matter, and also can account for disturbances such as fire and logging.

"By combining the capabilities of CENTURY and our knowledge of the distribution of forest types and climate zones, we estimated a value for the net ecosystem production of carbon for the five major tree species in Alaska's boreal forest," Yarie said. The major ecosystem types, ranked from most

prevalent to least, are black spruce, white spruce, birch, aspen, balsam poplar, and black cottonwood.

Whether an ecosystem is a source of atmospheric carbon or a sink where carbon is sequestered is determined by the relationship between production and decomposition. Climate warming could increase the number and size of trees, so that more carbon dioxide in the atmosphere would be converted to plant material and oxygen. A greater biomass of forest would also produce more material subject to decay. If climate warming promotes organic matter decomposition, this could increase soil respiration and the amount of carbon dioxide released to the atmosphere.

The study used inventory data from the U.S. Forest Service Inventory Analysis Unit to estimate the land area represented by the major overstory species at various age classes of trees. The CENTURY model was then used to develop an estimate of carbon dynamics throughout the age sequence of forest development for the major ecosystem types.

The maximum net primary production was estimated for various ecosystem types with a current climate scenario and a climate warming scenario. The model predicted that a 5° centigrade increase in the mean annual temperature, with no change in precipitation, would increase the net ecosystem production estimate of carbon for the taiga forest of Alaska by 16.95 teragrams (Tg) a year. A teragram equals one trillion grams.

Yarie's research background is in forest nutrient cycling and plant-soil relationships. He is also interested in applying site-specific knowledge to landscape level problems through the use of modeling and geographic information systems. He teaches forest ecology, theoretical ecology, and research methods, and directs the Forest Soils Laboratory. He can be reached by e-mail at: [ffjay@uaf.edu](mailto:ffjay@uaf.edu). Also see Yarie, J. and S. Billings. 2002. Carbon balance of the taiga forest within Alaska: present and future. *Canadian Journal of Forest Research*. 32: 757–767.

For more information see the websites of the Alaska Boreal Forest Council: <http://www.akborealforest.org/>; the Boreal Ecology Cooperative Research Unit: <http://www.becru.uaf.edu/default.htm>; Bonanza Creek Long Term Ecological Research: <http://www.lter.uaf.edu/>.

# Climate and Growth in the Boreal Forest

Studies correlating climate records and tree-growth in the boreal forest have important implications for predicting future growth and aboveground carbon storage under various climate scenarios. The Alaska boreal forest is one of the largest forest regions in the United States, is largely free of human disturbance, and has experienced a major climate warming since the 1970s. In work by Glenn Juday and Valerie Barber, hundreds of tree disks and cores were collected from black and white spruce and birch throughout interior Alaska to determine climate sensitivity, future growth scenarios under a warming climate, and potential for carbon credits and storage. While he was a doctoral candidate, recent graduate Martin Wilmking has also collected over one thousand cores from treeline white spruce in the Brooks and Alaska ranges.

Most of the samples collected are five millimeter cores taken to the center of the tree at breast height or as low on the tree as feasible. Any disks collected were from trees that were being cut down for other purposes. A tree is typically not sacrificed to measure radial growth. The coring technique is nondestructive and doesn't hurt the tree.

Although boreal tree growth sometimes increases with climate warming and treeline is advancing in some regions, recent studies at the Bonanza Creek Long Term Ecological Research site (BNZ LTER) and elsewhere show that the effects of warming on the boreal forest will probably be more negative than positive. Ninety-five percent of the Alaska boreal forest consists of stands dominated by three tree species, black spruce (55%), white spruce (25%), and birch (14%). For all three species, at least some sites hold evidence of decreased radial growth from warming temperatures.

Interior upland white spruce trees are consistent in their negative growth response to warming summer temperature. Black spruce and birch show some mixed sensitivity. A negative growth response to temperature means that warmer temperatures produce less radial growth. A positive growth response to temperature means the warmer the temperature, the better the radial growth.

Different climate indices are developed for the different species and also for different sites. A climate index is created by running correlation analyses between average radial growth per year by site against monthly average temperatures. Sometimes more than one month is statistically correlated with growth, so an index must be made of those months. For example, interior Alaska white spruce show a strong negative correlation to summer (May–Aug) temperatures, so an index of summer temperature is created by averaging the mean monthly temperatures from May, June, July and August. This new average is a climate index for summer temperature. “We can create an index for each year of recorded climate date,” said Barber, “and Fairbanks has one of the longest climate records, dating



Valerie Barber coring a white spruce. Photo by Doug Schneider.

back to about 1904.” Since many of the other interior Alaska recorded climate sites correlate well with Fairbanks climate data, the Fairbanks climate data is often the one of choice for sensitivity studies in Alaska.

A study on twenty different low elevation upland white spruce sites in interior Alaska, which was published by *Nature* in June 2000, showed that all sites had a negative radial growth response to summer temperature. A regime shift occurred in the mid to late 1970s, where the summer climate in interior Alaska went from cool and moist to hot and dry. During the cool and moist period, the white spruce from these sites grew well. The warm and dry summers were particularly detrimental to the radial growth of white spruce.

A study conducted by Wilmking shows that high elevation treeline white spruce show mixed sensitivities to climate. He found that approximately forty percent of the trees responded with negative radial growth to warmer summer temperatures, forty percent showed positive radial growth to warmer spring temperatures, and about twenty percent showed no sensitivity. This study has broad implications for predicting treeline advance, because it demonstrates that under a warming climate, some populations of treeline trees will grow markedly less, and perhaps not even be able to grow at all on some types of sites.

“The recent find that Alaska black spruce trees are highly sensitive to climate and have a number of different climate indices that optimize growth is surprising,” Juday said. “It indicates that black spruce trees occupy sites with more varied environmental conditions than previously thought.”

Growth of slope and ridge-top black spruce is negatively related to early and late summer temperatures at Fairbanks; the trees grow best in cool summers and least in warm summers. This indicates that climate warming of 2–4° C would probably result in the death of some black spruce populations in Alaska. Growth of valley bottom black spruce on permafrost is both positive to winter temperature and negative to early spring (April) temperature. Growth of black spruce on Tanana Valley surfaces near Fairbanks responds positively to midwinter temperatures. These populations will probably do well for a time under increased warming, but most black spruce trees are found on permafrost sites. With thawing permafrost,

predictability of growth or survival of black spruce is unreliable.

Preliminary studies of Alaska birch show that it too responds to climate depending on site. Birch, which is considerably more productive on average than black spruce, is the third most extensive forest type in Alaska, and birch-dominated stands make up about fourteen percent of the boreal forest. “Very little research about birch growth has been published, and practically none relating to how its growth is controlled by climate,” Juday said.

Tree-ring samples were collected from about 174 Alaska birch trees at four sites in the Fairbanks area. There are several challenges to working with birch. Wood decay and rot is so common in mature Alaska birch that only one in four sampled trees produced usable cores. Because radial growth of Alaska birch is highly irregular, two to four radii per tree are needed to accurately measure annual growth. This means that at least two different cores from different sides of the tree must be taken and measured for an average, or if a disk is obtained, radial growth will be measured from bark to pith at two or three different points (sides) of the trunk and then averaged. Typical birch stands around Fairbanks have dates of origin in the 1930s. The Live Birch reference hectare at the BNZ LTER site contains birch with a measured date of origin at about 1810. In many birch trees, growth in certain years practically ceased (1877–78, 1921, and 1970 for example), producing rings that are difficult to distinguish.

Although measurement of birch tree-rings is much more difficult than either white or black spruce, previous experience with the spruces allowed staff at the SNRAS tree-ring laboratory to successfully identify and sequence tree-rings in the birch sample. Although different climate indices optimize growth according to site, summer temperatures appear to have the greatest effect. Radial growth of birch trees sampled from several south-facing slopes near Fairbanks indicates a high negative correlation with summer temperature: warmer temperatures induce reduced growth.

“In a sample of forty-seven birch from the two stands, radial growth was highly negatively correlated with May through August Fairbanks temperature,” said Barber. “This suggests that recent summer warmth has reduced and future warming would reduce radial growth of this species.” The growth of older birch on an east-facing slope in Bonanza Creek LTER showed a positive correlation with individual summer months over a three-year period, indicating that trees on this site will do better with warmer summer temperatures.

The relationships between climate and growth for these three major boreal forest species are statistically strong enough that they can be used to develop empirical equations and excellent predictive relationships.

“All sites sampled to date register some form of climate



sensitivity in at least some trees. For most of the sites, we have observed statistically significant relationships between climate and tree growth, and these allow us to predict future growth under various climate scenarios,” Barber said.

Participation by Juday and Barber in the Arctic Climate Impact Assessment, a circumpolar project, allowed them to obtain predicted monthly climate output data from five Global Climate Models up through the year 2099. The empirical relationships developed from the climate

sensitivity studies and used in conjunction with these global climate models was used to predict annual radial growth of these three species. Results show that some populations of white and black spruce and birch would not survive at all, because their growth rates would actually approach zero within seventy to one hundred years.

The first generations of vegetation models assumed that warming would cause an increase in boreal forest growth. “Because our findings have broad implications for carbon uptake and aboveground carbon storage, it is important that dynamic vegetation models incorporate this new information,” said Juday.

Boreal forests are a significant factor in world carbon uptake, and forest stands dominated by black spruce make up over half of Alaska’s boreal forest cover. “Despite the generally small size and slow growth of individual black spruce, the total area they cover, and their total volume, make them an important species when looking at potential changes of carbon uptake in Alaska,” Juday said.

The aboveground carbon biomass, which is the weight (Mg/ha or kg/m<sup>2</sup>) of the aboveground portion of the tree, is determined by oven drying the samples until a constant weight is reached. To do this accurately, there must be a consistent allometric relationship between plant dimensions (usually diameter at breast height (dbh) and/or height) and biomass for a given species or growth form. Barber and Juday usually rely on published allometric relationships by species. The carbon weight is typically about fifty percent of the dry weight.

The research discussed here was funded in part by the U.S. Department of Energy, the National Science Foundation’s LTER program, and a USDA “New Crops Opportunities” grant from the Cooperative State Research Education and Extension Service. For more information, contact Glenn Juday (ffgpi@uaf.edu) or Valerie Barber (barber@ims.uaf.edu) at the School of Natural Resources and Agricultural Sciences.

—Doreen Fitzgerald with Valerie Barber

## References

See the original article in *Agroborealis* 5.2. Available in pdf format on AFES publications page for *Agroborealis*: <http://www.uaf.edu/snras/afes/pubs/agro/index.html>.



## soil — the dark laboratory

*Areas of permafrost along the Innoko River. Photo courtesy of the U.S. Fish and Wildlife Service.*

Soil, the dynamic, biologically active layer of Earth's continental surface, sustains life through its biogeochemical and hydrologic processes. In grade school, we all learned that decomposition in soil is necessary for recycling nutrients into forms available for plants—without it, dead things would pile up indefinitely. Decomposition also makes soil a major player in the global carbon cycle.

To understand how life in soil matters to the global carbon cycle, we first need to review respiration. All living things respire; that is, they metabolize energy-rich compounds and usually release carbon dioxide (CO<sub>2</sub>) as a result. The source of those compounds determines whether the respiration is termed autotrophic, as in the case of plants making their own “food” during photosynthesis, or heterotrophic, as in the case of most other living things that rely on outside sources (ultimately plants) for theirs.

Autotrophic respiration occurs in living plants, both above ground and below ground through plant root systems. Heterotrophic respiration occurs through the consumption of live plant parts and the decomposition of dead plant residues. Both kinds of respiration occur in soils—autotrophic respiration from plant roots and heterotrophic respiration from soil animals and microorganisms, including decomposers.

The problem soil scientists face in understanding the role of soils in carbon balance is that while it is easy to measure total soil respiration (i.e., CO<sub>2</sub> emission), it is difficult to separate autotrophic from heterotrophic sources. And only the heterotrophic component affects carbon balance. The exact proportion each of these contribute to total ecosystem respiration varies a great deal from place to place, although the heterotrophic respiration resulting from decomposition is thought to make up roughly half of the total global carbon dioxide emitted by terrestrial ecosystems.

The general factors determining respiration are well understood. In living plant roots, autotrophic respiration is related to their overall productivity and how they allocate the photosynthate (sugars) produced by photosynthesis. Carbon

dioxide release through decomposition (heterotrophic respiration) relates to factors that control microbial activity: temperature, moisture, and the type and amount of material subject to decay.

Largely unknown is exactly how these factors combine to affect soil respiration at a given point in time. This is due to the complexity of interactions in soil and the variability of organisms present, type of plants and their strategies, micro-environmental conditions, and such other factors such as site history, soil mineralogy, nutrient availability, and types of plant litter. Depending on these factors and climate, soil organic matter can be either a source of, or a sink for atmospheric CO<sub>2</sub>. It is a sink if carbon inputs from plants exceed heterotrophic respiration, otherwise it is a source.

Current research by faculty and graduate students at the School of Natural Resources and Agricultural Sciences is aimed at closing some of these information gaps for high-latitude soils. Among the questions now being explored are how changes in disturbance regime and in climate affect carbon balance in black spruce stands. Of high interest in light of climate warming projections is how the north's perennially frozen soil, permafrost, will respond to warmer temperatures. Although twenty to twenty-five percent of Earth's land surface is underlain by permafrost, scientists are uncertain how warmer temperatures might affect it, or how thawing ground ice could affect everything from local ecology to regional climate. Could warmer, wetter weather, for example, increase vegetation growth, insulating the permafrost and keeping the near-surface ground layers frozen? Or, will melting permafrost cause these soils to release sequestered carbon into the atmosphere as carbon dioxide? Because permafrost may vary dramatically from region to region, scientists are studying its properties over large geographic areas. The studies covered in the following pages illustrate how researchers are tackling these questions and what they have found to date.

—Doreen Fitzgerald with David Valentine

# Black spruce and soil carbon exchange

Trees are a major consumer of atmospheric carbon dioxide (CO<sub>2</sub>). They store the carbon as organic matter in their tissues and also deposit carbon in the soil. This makes forests important repositories for the CO<sub>2</sub> coming from human fossil fuel burning. In Alaska, ecosystems with black spruce as the major trees species are the most common, followed by white spruce, birch, and mixed spruce stands.

Black spruce forests grow slower than other boreal forest types, but they end up storing more carbon because cold and wet soil conditions restrict the decomposition of organic matter. An important question is whether and how black spruce forest soils will alter their soil carbon balance (net carbon loss or gain) in a warmer climate. Although climate warming is expected to have the greatest effect at high latitudes, there are considerable information gaps related to how much carbon trees allocate below ground for roots, the rate microbes decompose organic matter, and what this all means for aboveground plant growth.

A study by doctoral candidate Jason Vogel and soil scientist David Valentine has provided some insight into the relationship between local climate and soil carbon balance. "Boreal black spruce and soil carbon exchange along an elevation gradient" is an ecosystem carbon cycling study that was conducted near Fairbanks, Alaska.

"The decomposition rate, or the rate microbes (microscopic soil organisms) turn organic matter back into CO<sub>2</sub> increases with temperature, so a warming climate is expected to accelerate soil carbon loss via soil respiration from cold boreal soils," said Vogel. "This should result in more carbon released into the atmosphere. But increased decomposition can also increase the nutrients available to plants and result in increased plant productivity. These factors could increase the storage of organic matter in plants and soil."

Vogel and Valentine looked at the relationship between decomposition and aboveground plant growth, total soil respiration, and the heterotrophic respiration that occurs during decomposition of organic material.

"We wanted to control for the effects of vegetation and look specifically at how soil environment affects decomposition and plant productivity, so we found sites that were similar in tree age, tree size, and number of trees," Vogel said. "Black spruce sites were selected for variation in slope orientation, elevation, and depth to permafrost, because these characteristics should create variability in soil temperature."

They hypothesized that as decomposition rates increase, both the ecosystem's aboveground uptake of CO<sub>2</sub> from plant photosynthesis, and the CO<sub>2</sub> loss from soil respiration (root respiration and microbial respiration from decomposing or-

ganic matter) will increase. In other words, warming will promote decomposition; as decomposition increases, the amount of CO<sub>2</sub> released from soil through respiration will increase, as will the uptake of carbon dioxide by plants. The result would be a balance between forest growth and decomposition with no net increase in the loss of carbon from the ecosystem.

To check this hypothesis, they looked at decomposition rates of black spruce needles and cellulose paper, and the heterotrophic respiration coming from areas where live roots had been eliminated (root exclusion). Soil respiration, or CO<sub>2</sub> release from the soil surface, was measured with a portable infrared gas analyzer both in and outside the root exclusion areas. The difference between areas was assumed to equal root respiration. Aboveground tree increment was measured by removing tree cores and measuring the tree ring width.

Faster decomposition correlated to greater heterotrophic respiration in the root exclusion areas and greater aboveground plant production. These two results suggest that ecosystems will not lose more carbon with warming, because decomposition is offset by plant production. However, contrary to their hypothesis, soil respiration (roots plus microbes) was greater where decomposition and heterotrophic respiration was the slowest. "We were initially surprised by the results, but realized that the plants were allocating less carbon to the root system, where decomposition was faster," Vogel said.

The researchers believe the black spruce allocates more carbon below ground when their growth is limited, either by low nutrient or moisture availability. "Greater allocation of carbon to roots probably indicates that spruce have to work harder at getting nutrients or moisture when the availability of these resources are limited," said Vogel, "and slower decomposition rate seems to be a good indicator of when black spruce puts more carbon below ground."

The researchers suggest that variability in aboveground growth might result from spruce shifting carbon allocation between above- and belowground plant parts when the environment changes. Shifting allocation seems to occur across the boreal forest. For example, they looked at other research in the North American boreal forest and found the amount of carbon cycling below ground changes drastically across a precipitation and evaporation gradient.

The observation that allocation shifts in response to environment changed their perspective on how climate change might influence carbon balance. Forests might remove the same amount of carbon from the atmosphere, but it ends up in a different place as a function of environment. However, the research points out that both temperature and moisture will be important to forest growth. "Research that manipulates soil moisture or temperature is necessary before we will know for sure how these forests will respond to climate change," Vogel concluded.

The research was funded by the UAF Center for Global Change and the Bonanza Creek Long Term Ecological Research program. For more information contact: Jason Vogel (ftjgv@uaf.edu) or David Valentine (ffdlv@uaf.edu).



*Aerial view of a prescribed burn in a conifer-dominated forest. Photo by David P. Shorthouse, University of Alberta, [www.forestryimages.org](http://www.forestryimages.org).*

## *soil respiration after fire*

Wildfire is a regular part of the summer season in Alaska, and unless it occurs in a protected area, it is allowed to burn unchecked. Frostfire, a project that in 1999 burned a carefully isolated experimental area, gave researchers the chance to study various conditions before, during, and after fire in the boreal forest.

Although the greatest proportion of the world's terrestrial carbon is found in wetlands, tundra, and alpine soils, the thick, mossy forest floor in boreal forests contains more carbon than temperate forests, tropical forests, or cultivated land. Most of this forest is in wilderness, and millions of acres worldwide burn annually. Knowing how this affects the release of carbon dioxide (CO<sub>2</sub>) from the soil is an important part of the global carbon picture.

David Valentine, associate professor of forest soils, decided to use the Frostfire burn to find out how wildfire in interior Alaska affects respiration and the carbon balance (net gain or loss of carbon) of soils. He hypothesized that since warmer temperatures tend to accelerate soil respiration, the burned boreal forest soils would release more carbon dioxide than unburned ones. This is because fire removes the tree canopy and creates large blackened areas, so soils in burned areas absorb more sunlight. Fire also removes much of the insulating moss layer, allowing soils to warm more during summer months. Warmer soils are expected to increase activity of soil micro-organisms and release more carbon dioxide (although root respiration would, of course, stop). This has proven to be the case when burned areas have been studied at lower latitudes. Valentine has discovered a different response in Alaska.

"Our measurements since the summer of 1999 have clearly shown a persistent and growing decline both in total and heterotrophic soil respiration in burned areas compared to control areas," he said. The research site is at the C4 watershed in the Caribou Poker Creeks Research Watershed.

For this research, soil respiration is being measured at three burned and three unburned black spruce sites. The basic approach to measuring soil respiration is to invert a chamber on the ground and measure the change in CO<sub>2</sub> concentration over

time. In this case, the researchers used a portable infrared gas analyzer (IRGA) that Tim Quintal had customized to fit into a backpackable weatherproof box. Tim is the research technician for the SNRAS Forest Soils Laboratory.

Respiration measurements in the research watershed began in 1998, paused for the fire in July 1999, then resumed and have continued each summer. At the same time, Valentine's group has monitored soil temperature and moisture, soil gas concentrations, and the rate at which decomposition of a standardized substrate (birch tongue depressors) occurs.

The results of this study shed light on key dynamics governing carbon balance following fire, which is the major disturbance type in interior Alaska. The roots of trees killed by fire no longer respire CO<sub>2</sub>, so Valentine expected an initial decline in soil respiration resulting from the loss of root respiration. In 2002 Valentine and his students began measurements to quantify the extent to which this loss of root respiration may account for the decrease in total soil respiration.

"Our results from 2002 indicate that root respiration accounts for most but not all of the decrease in soil respiration, suggesting that fire also decreases the contribution of heterotrophic respiration (decomposition of organic matter) to total soil respiration," he said.

## *Fire and soil carbon bioavailability*

Valentine is working with graduate student Sarah Masco on a study to understand whether fire-induced changes in organic matter quality in surface soils is consistent with the observed changes in heterotrophic respiration. At the Frostfire site, soil samples were obtained from the lower part of the organic surface horizon. Subsamples from each layer were incubated in the laboratory at three temperatures for six months. Respiration rates, total amounts of respired CO<sub>2</sub>, and the temperature sensitivity of respiration rates were determined, then compared with chemical analyses of the soil organic matter.

The results showed that soil organic matter from burned sites respired slightly but significantly more slowly than soil organic matter from unburned control sites, especially early in the incubation period. Differences in respiration rate and temperature sensitivity did not correlate well with measured soil organic components. Burned soils had higher net nitrogen mineralization rates than unburned soils, possibly as a result of lower immobilization (microbial uptake of nitrogen) rates.

"This study points to a mechanism by which wildfire may reduce decomposition (heterotrophic production of CO<sub>2</sub>) in boreal forests, thereby limiting post-fire release of carbon," Valentine said. "That mechanism is the lack of recent fresh carbon inputs into the soil surface horizon."

These two studies were supported by the National Science Foundation through the Frostfire project and the Bonanza Creek LTER program.

—Doreen Fitzgerald

# Digging up facts on northern soils

In the past, the amount of soil organic carbon in high-latitude soils was underestimated, as was the significance of a winter contribution of carbon dioxide (CO<sub>2</sub>) to the atmosphere from alpine and arctic regions. As a result of recent research, it is now understood that both factors have important implications for the assessment of the potential effects of climate warming. Under a continuous buildup of greenhouse gases in the atmosphere, general circulation models already predict climate warming that at high latitudes may be several times greater than the global average, and possibly more pronounced in the winter.

About one-third of Earth's soil organic carbon is locked in tundra and boreal soils because of cold temperatures, and past trace gas budgets have assumed that trace-gas exchange between soil and atmosphere stops when soil temperatures decrease to zero degrees centigrade. For this reason, the contribution of CO<sub>2</sub> from alpine and arctic regions in winter has not been considered important in calculations of global carbon balances. Now, recent National Science Foundation (NSF) C-Flux winter monitoring studies have identified large quantities of CO<sub>2</sub> efflux from arctic soils during the winter period. This previously overlooked contribution could amount to as much as sixty percent of the annual CO<sub>2</sub> efflux. To account for winter in carbon balance models and calculations, the need for information about quality, quantity, and distribution of soil organic carbon in the Arctic is now fully recognized.

At the Palmer Research Station of the Agricultural and Forestry Experiment Station, professor of soil sciences Chien-Lu Ping and research associate Gary Michaelson are participants in an effort to obtain this information, the Land-Atmosphere-Ice Interaction (LAI) program. LAI is a multidisciplinary, integrated research effort funded by the NSF and conducted under the auspices of the foundation's Office of Polar Programs, Arctic System Science (ARCSS) program. ARCSS is the only element of the U.S. Global Change Research Program specifically concerned with the arctic region.

Information crucial for evaluating potential climate warming effects includes: the quality and quantity of organic matter in these soils, rate of microbial decomposition at below-zero temperatures, and the mechanisms that control the rate of low-temperature microbial decomposition.

The LAI goal is improved understanding of the interactions among land, atmosphere, and ice in the functioning of the Arctic System, with emphasis on improving the predictability of likely responses of the Arctic System to global change. Because these interactions are broad and complex, the research program strongly emphasizes integrated research that brings together scientists from multiple disciplines, including biology, hydrology, ecology, climatology, paleoecology, and soil science.



*Ping and Michaelson sampling soils near Galbraith Lake, Alaska.  
Photo courtesy of Chien-Lu Ping.*

## Winter carbon flux study

From 1999–2003, the LAI-ATLAS (Arctic Transitions in the Land Atmosphere System) Winter C-flux study was conducted by NSF. It was designed to develop a sufficient understanding of winter carbon dynamics in arctic soils to effectively model the spatial dynamics of winter CO<sub>2</sub> fluxes, and how they will vary with altered climate. The work involves field measurements of CO<sub>2</sub> fluxes and environmental factors likely to control them, along with modeling and mechanistic studies.

The project's four main objectives are to quantify the magnitude and timing of winter CO<sub>2</sub> fluxes across a range of arctic tundra types; determine how winter respiration is controlled by the physical regime of the soils; evaluate how organic matter composition controls winter carbon cycling; and develop simple models of winter microbial activity. These objectives link the soil thermal and unfrozen water regimes to microbial activity and substrate use. The over-arching goal is to develop the simplest possible models that can be driven by broad scale parameters, while retaining necessary mechanistic information to provide reliable estimates of carbon dynamics.

Earlier field investigations determined that arctic soils contain about twice as much of the terrestrial carbon pool as previously reported, and that the major portion occurs in the lower active layer and upper permafrost layer. The soil active layer is that portion of the soil that is subject to seasonal freeze and thaw, rather than perennially frozen. These results were published in the journal *Arctic and Alpine Research*. Recent research conducted by Ping, Michaelson, and colleagues from the University of California Santa Barbara and Colorado State University has demonstrated that in these soils, trace-gas exchange from microbial activity does not stop during winter, and that a positive feedback of some arctic ecosystems to climate warming may be due to the efflux of substantial amounts of soil carbon to the atmosphere.

Using eighty-eight arctic soils collected from twenty-eight sites spanning hundreds of miles, Michaelson and Ping completed a study under ATLAS that has answered some important questions. After determining the properties (quality

and quantity of organic material) of their soil samples, they incubated them at low temperatures in the laboratory and measured carbon dioxide respiration. They found that respiration rates varied considerably, depending on a sample's organic carbon content, organic matter quality, and whether the experimental temperature was a few degrees above or below zero degrees centigrade (4° C and -2° C). When temperatures dipped below freezing, subsoils from the active layer and upper permafrost that contain large amounts of cryoturbated organic matter (mixed in by frost action) were found to maintain relatively high rates of CO<sub>2</sub> efflux compared to the organic surface soils.

"Our results suggest that relatively small changes in temperature will alter cold-season respiration throughout the soil active layer," Ping and Michaelson concluded. The research was published in the *Journal of Geophysical Research*.

## Soils dataset

Ping, Michaelson, and Kimble reported in 2002 that for the first time, soils data (morphological, physical, and chemical) were available for sites across arctic and subarctic Alaska. The first soils dataset for arctic Alaska resulted from extensive field investigations, a cooperative research effort funded by the NSF, the U.S. Department of Agriculture (USDA) Hatch program and the USDA National Soil Survey Center. See "More Information" at the end of this article for data availability. This soils information is being used in the integrated research projects of NSF-LAII: C-Flux, ATLAS, Circumpolar Active Layer Monitoring (CALM) project, and the USDA Global Change Initiative projects that are examining arctic and subarctic terrestrial systems.

"These investigations were important in field-testing the newly adapted Gelisol order in Soil Taxonomy, in supporting ongoing soil survey projects in Alaska, in the development of the Circumpolar Soils Map and the North American Soil Carbon Map. The dataset is also important for climatic modeling efforts," Ping said.

*Gelisols* are soils of very cold climates that contain permafrost within two meters of the surface. They account for approximately thirteen percent of the earth's land surface area and are in the high-latitudes polar regions and localized areas on high mountains.

## Soil organic carbon

Thus far, detailed and specific studies of soil organic carbon (SOC) stocks under the ARCSS-LAII programs indicate that arctic soils contain twice as much of the terrestrial carbon pool as previously reported. This newly accounted for SOC is significant, not only in magnitude, but also in its quality as it relates to arctic and global carbon cycles under changing climate.

Organic matter characterization study indicates that soil active layers contain relatively large amount of their carbon in fractions that are in an intermediate state of decomposition and are susceptible to further decomposition under warmer temperatures and changing moisture levels.

Large amounts and proportions of SOC stocks are found in both the active-layer and upper permafrost due to cryoturbation (soil mixing due to frost action). Because this large

portion of soil organic carbon is not highly decomposed, it is susceptible to increased decomposition with warming winter and shoulder-season conditions such as those that are now being observed in arctic Alaska.

For the circumpolar Arctic, this research provides a basis for future work to link terrestrial carbon flux to soil carbon stocks and quality. ATLAS research thus far has laid the soils groundwork for such a link and provided data that is important to all facets of the project. It is now recognized that winter soil processes are the key to understanding whole-season carbon fluxes in the arctic system. This illuminates the need for further research on soil processes, soil carbon cycles, and their controls in the context of soil-landscape evolutionary processes.

## Soils associated with arctic frost boils

Ping and Michaelson are participating in another NSF multidisciplinary project titled "Biocomplexity of Frost Boil Ecosystems." Cooperating scientists are Donald (Skip) Walker of the UAF Institute of Arctic Biology, Vladimir Romanovsky, UAF Geophysical Institute, Charles Tarnocai of Agriculture and Agri-Food Canada, and others (see <http://www.geobotany.uaf.edu/cryoturbation>).

This project is looking at the role of frost boils in ecosystems ranging from the Canadian high Arctic to Alaska's north slope. Frost boils are formed by differential frost heave, and are unsorted circles of mineral soil commonly found in alpine and arctic regions. On the ground, the fresh soils form a circle or stripe that looks like a mud "boil" surrounded by tundra vegetation. Carbon sequestered in frost boils accounts for at least one-half of the total terrestrial carbon stored in arctic ecosystems, and has not been reported before this research. In early studies, frost boils were found more frequently in the land cover type moist nonacidic tundra (MNT) than the moist acidic tundra (MAT) of the Arctic Coastal Plain and the Arctic Foothills of Northern Alaska.

For this study, soils investigation sites were selected in association with the vegetation plots of the NSF Biocomplexity project. Complete morphological descriptions of the soils are being made to follow the USDA Soil Survey Manual. Soil samples from each horizon are sent to the UAF-SNRAS Palmer Plant and Soils Analysis Laboratory for detailed physiochemical and nutrient analysis and to the USDA Soil Survey Laboratory in Lincoln, Nebraska, for physical and chemical characterization using the USDA National Soil Survey laboratory standard procedures.

"Our preliminary results indicate that frost boils are actually widespread in both land cover types," Ping said. "On the surface, there appear to be more fresh frost boils in the MNT than MAT, but we found that more frost boils occur under the MAT, where they are masked by vegetation cover."

The active layer is deeper under the boil than under the area between the frost boils. In cross section, the frost boil is defined by a bowl shape indented into the top of the permafrost table. Although frost boils in the MAT are not as evident in surface vegetation patterns, they are still active, as indicated by chunks of cotton grass (*Eriophorum vaginatum*) found at various stages of decomposition and in the process of being frost-churned downward along the slopes of the "bowl" onto

the top of the permafrost table.

“In the lower active layer and upper permafrost,” said Ping, “a concentration of frost-churned organic matter mixed with gleyed mineral horizons occurs. Thus, the frost boil process can be regarded as a controlling factor for sequestering surface organic carbon into the upper permafrost.” Frost boil processes and resulting soils are much more important than previously recognized for their role in the carbon-cycle of arctic ecosystems.

## Biocomplexity of frost boil ecosystems:

### 2003 expedition

A major goal of the biocomplexity study is to help explain how frost boils and arctic vegetation will respond to climate change. The study team includes the previously mentioned Walker (project leader), Ping, Michaelson, Romanovsky, and Tarnocai, along with Martha Reynolds of the UAF Institute of Arctic Biology, Anja Kade of the UAF Biology Dept., Howard Epstein and Alexia Kelly of the University of Virginia Dept. of Environmental Sciences, William Gould and Grizelle Gonzalez from the International Institute of Tropical Forestry, USDA Forest Service (San Juan, Puerto Rico), and William Krantz of the University of Cincinnati Dept. of Chemical Engineering.

The team is interested in the self-organization processes involved in frost-boil formation and how the complex interactions between the elements involved in frost-boil formation (frost heave, vegetation, and soil properties) vary along the arctic bioclimate gradient.

Study sites are being established in each of five circum-polar arctic bioclimate subzones; Subzone A is the coldest and Subzone E is the warmest. In Alaska the study sites include Howe Island, West Dock, Deadhorse, Franklin Bluffs, Sagwon Hills, and Happy Valley.

In July 2003, the team began setting up its Canadian network at a site on Banks Island, near Green Cabin in Aulavik National Park and at Mould Bay, Prince Patrick Island. Most of the 2003 work was at Banks Island, which is in Bioclimate Subzone C, an area where the zonal vegetation consists of prostrate dwarf shrubs, sedges, and a few forbs, mosses, and lichens. The interdisciplinary project has five major components: (1) Climate and Permafrost, (2) Soils and Biogeochemical Cycling, (3) Vegetation, (4) Ecosystem Modeling, and (5) Education.

The team characterized the frost boils, vegetation, and soils within three 10-meter by 10-meter grids along a toposequence. The education component was an Arctic Field Ecology course offered through the University of Minnesota. Frost boils on zonal sites had similar morphology to those on Howe Island, and other Subzone C sites. The frost boils on zonal sites were of one to two meter diameter (30 frost boils/100 m<sup>2</sup>). The frost boils were nearly barren with only a few scattered grasses and forbs. The inter-boil areas had more continuous cover of vegetation consisting of a mountain avens (*Dryas integrifolia*) community. *Dryas integrifolia* is a dwarf shrub in the rose family. A strong thermal gradient existed between the barren boils and well-vegetated inner-boil areas, particularly in the wet site. The soils show strong mixing with abundant carbon in the active layer and in the top portion of the permafrost. Covering the

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inter-boil areas and extending into the boils themselves were small hummock features (20–50 cm diameter), caused by either thermal-contraction within the active layer or desiccation. In July the soils study group (Ping, Michaelson, and Tarnocai) characterized and sampled eight sites and collected seventy-five samples from Banks Island.

In August Ping organized another team to study soils associated with frost boils in arctic Alaska. It included Michaelson, John M. Kimble of USDA-NRCS National Soil Survey Center, Lynn Everett of Ohio State University, UAF forest management professor Edmond Packee, Norman Bliss of the U.S. Geological Survey, and resources management graduate students Carolyn Rosner and Patrick Borden. The group studied five sites and collected forty samples from arctic Alaska. These samples are being analyzed in the Palmer Research Center and also the USDA National Soil Survey Center Lab. Information from Alaska and Canada will be used to develop models of the interactions between frost-heave processes, vegetation and soil biogeochemical processes.

### More Information

For more information, contact Chien-Lu Ping ([pfelp@uaa.alaska.edu](mailto:pfelp@uaa.alaska.edu)) or Gary Michaelson ([pngjm@uaa.alaska.edu](mailto:pngjm@uaa.alaska.edu)) at the Agricultural and Forestry Experiment Station Palmer Research Center. Also see the following websites and references.

Alaska Geobotany Center (<http://www.geobotany.uaf.edu>)

NSF LAII (<http://www.laii.uaf.edu/>)

Cryosol Working Group of the International Union of Soil Science and the International Permafrost Association (<http://igras.geonet.ru/cwg/>).

The soils datasets are available through the National Snow and Ice Data Center (<http://nsidc.org/data/arcss074.html>) and also on the center's Ivotuk and Seward Peninsula CDs, the NSF Joint Office of Science Support ([http://www.joss.ucar.edu/atlas/master\\_data\\_table.html](http://www.joss.ucar.edu/atlas/master_data_table.html)), and through the USDA Natural Resource Conservation Service soils database: <http://ssldata.nrcs.usda.gov/querypage.asp>.

### References

See the original article in *Agroborealis* 35.2. Available in pdf format on AFES publications page for *Agroborealis*: <http://www.uaf.edu/snras/afes/pubs/agro/index.html>.